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WITH A PREFACE BY T. W. EDGEWORTH DAVID.

BY E. C. ANDREWS.

WITH FORTY PLATES.

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No. 1. — *Notes on the Limestones and General Geology of the Fiji Islands, with Special Reference to the Lau Group. Based upon Surveys made for* Alexander Agassiz. By E. C. Andrews.

INTRODUCTORY NOTE

By Alexander Agassiz.

After my exploration of Fiji during the winter of 1897–98, it became evident that many of the problems which suggested themselves while passing from island to island could only be solved by a careful examination of well-selected localities representing the typical structures of the islands and coral reefs of Fiji.

It seemed best that the selection of a well-equipped explorer should be made from Australasia, and I naturally turned to Professor David of Sydney for advice; he most kindly interested himself in the project. At his recommendation, Mr. E. C. Andrews, assisted by Mr. B. Sawyer (both of the University of Sydney), consented to undertake the exploration of the most accessible and interesting of the Fiji Islands.

The collections made by Mr. Andrews have safely arrived in Cambridge; they will be worked up in connection with the collections which I made myself in Fiji, and at the same time with a mass of similar material collected during the last expedition of the U. S. F. C. S. "Albatross" in the Tropical Pacific from August, 1899, to March, 1900.

The limestones collected by the "Albatross" represent material brought together from the Paumotus, Niue, the Tonga Islands, and Guam. Of course, a considerable time must elapse before this large collection can be properly examined and the results compared with those obtained by Mr. Hill and myself from an exploration of the reefs and the elevated limestones of the West Indian area (Bermudas, Florida, the Bahamas, Cuba, Jamaica, San Domingo, and the Windward Islands).

I intended to publish the report of Mr. Andrews with a running commentary based upon my exploration of Fiji, but with the wider experience lately gained in the Tropical Pacific, it seemed best to issue that report with few comments, and in the final report on the coral reefs of the Tropical Pacific to take up the subject again and thus not duplicate now the report on the results of the last "Albatross" expedition.

As Professor David has examined not only the collections made by Mr. Andrews, but also his report, I herewith add the greater part of a letter he was kind enough to write me relating to the collections and report of Mr. Andrews. This report, taken in connection with the monograph of Christmas Island[1] (Indian Ocean) undertaken at the instigation of Sir John Murray by Mr. Charles W. Andrews, illustrates how complicated a question the formation of an atoll is, even when we are able to follow its stages in the pages of the history of its elevation. And nothing shows more distinctly than the sections of Mango, of Tuvuthá, and of Singatoka, given by Mr. E. C. Andrews, how insignificant is the part played by corals in the economy of an atoll.[2]

NEWPORT, RHODE ISLAND,
August, 1900.

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[1] London, 1900. Printed by order of the Trustees of the British Museum.

[2] Charts of the Fiji Group and islands of the group will be found in "The Islands and Coral Reefs of Fiji." Bull. Mus. Comp. Zoöl., 1899, Vol. XXXIII., Plates 1–23a.

PREFACE.

LETTER FROM PROFESSOR T. W. EDGEWORTH DAVID OF THE UNIVERSITY OF SYDNEY, NEW SOUTH WALES, DATED MARCH 15, 1899.

MR. E. C. ANDREWS, B. A., is forwarding to you by this mail for your information his notes, maps, sections, and photographs relating to the geology of the raised reefs of Fiji, with some additional notes on Tonga.

This information he gained by personal examination of all the islands referred to in his report, and he and Mr. B. Sawyer, B. E. (also of Sydney University), who accompanied him, spared no pains in attempting to carry out your instructions as fully as possible.

With the funds placed by you at his disposal, Mr. Andrews was enabled to hire a cutter and a Fiji crew, and by this means he managed to visit most of the islands of the Lau Group and also explored Vatu Leile, part of Viti Levu, Taviuni, Totoya, etc.

His method of work after landing on an island was to explore the cliff faces and inland terraces, measuring altitudes and distances with an aneroid and Abney's level, by pacing and taking angles with a prismatic compass, and systematically collecting specimens by blasting and quarrying.

This cliff exploration was done at first by means of a strong wooden box lowered over the cliffs by a rope. This method was discarded for the simpler one of scaling the cliffs, after the manner of the Fiji natives, by means of the long rope-like roots of the banyan-tree, which depended in some cases for over one hundred feet in length over the cliffs.

After the sections of the cliffs had been obtained and systematic collections of specimens made, the higher slopes and inland terraces of the islands were explored, it frequently being necessary to cut tracks through the dense undergrowth for a considerable distance, in order to admit of the ground being traversed.

Mr. Andrews' short report and notes and sections speak for themselves, but at the same time I should like to say a few words about his general conclusions.

He finds the following formations represented in Fiji, the older being mentioned first : —

(1) Bluish gray hard limestones without macroscopic fossils, and dipping at steep angles. This was seen only in the Singatoka area, Viti Levu, where it underlies the bedded foraminiferal limestone.

All the specimens of this have been forwarded to you, and this rock, as being probably the oldest hitherto observed in Fiji, should be worthy of careful microscopic examination. It may possibly have some relation to the Globigerina limestone of the Solomon Islands, and that recently brought to Sydney by Mr. Danvers Power from Noumea in New Caledonia, which is also a Globigerina limestone.

(2) Volcanic rocks, such as spherulitic rhyolites and diabasic dolerites, which must have supplied the well-rolled pebbles in the conglomerates of the Fiji soapstones.

(3) (*a*) "Bedded limestones." These are developed, as observed, by Mr. Andrews chiefly at the Singatoka area. Their angle of dip is 15°, and they are largely foraminiferal (forms like Amphistegina, Globigerina, Textularia, etc., being well represented), mixed with fragments of nullipores, gastropod and lamellibranch shells, polyzoal skeletons, fragments of echinus spines, etc. As you will see from the specimens sent, this is distinctly not a coralline limestone, but rather a foraminiferal nullipore rock. If the planes of bedding represent originally horizontal planes which have been subsequently tilted so that they now dip at 15°, the thickness of these bedded limestones at the Singatoka area, as measured by Mr. Andrews, cannot be much less than 1500 feet.

Outcrops of similar limestones have been observed by Mr. Andrews at the raised atoll of Mba Vatu, Vanua Mbalavu, in the Lau Group, where they form the foundation rock upon which the raised limestone rock rests.

(*b*) Calcareous fossiliferous volcanic conglomerates probably passing in places into the "soapstone" formation of Fiji, the latter being a foraminiferal submarine volcanic tuff and tufaceous foraminiferal mudstone.

These may be slightly newer than, or possibly contemporaneous with, the foraminiferal "bedded limestones" of the Singatoka area.

In the Lau Group they are seen at Mango, where, as shown on the left-hand side of the upper of Mr. Andrews' sections, they form the basal rock on which the raised reef limestone rests (Plate **2**).

A thickness of only about four feet is exposed at Mango. They appear to be associated in places at Mango, as observed by Mr. Andrews, with a steatitic fine basic tufaceous rock, homotaxial perhaps with the Suva "soapstone."

(*c*) Fiji "soapstone" with interstratified coral reef and coral detritus, as well as one bed of coarse well-rolled pebbles of volcanic rocks. This formation is at least three hundred feet thick, and its base is not visible. It exhibits in places, as at Suva, a dip of about 10°.

As you have ample material for a detailed description of this remarkable tufaceous marine mudstone, I will make only the few following remarks about it: (1) That on certain horizons in Suva at over a hundred feet above sea-level I noticed thin interstratified bands, almost wholly formed of angular crystals of augite and plagioclase and of lapilli of decomposed basic lavas, from the size of a hazel-nut to that of a walnut. There appeared to me to be every gradation in this soapstone from a true submarine tuff to a slightly tufaceous foraminiferal rock, and from the latter rock into a tufaceous detrital coralline limestone.

In one spot at Walu Bay a small coral reef is interstratified with the soapstone, as already mentioned in your paper.[1] Professor Sollas has referred to this as indicating that some, at all events, of the soapstone was laid down in shallow water, and is not, as Mr. G. B. Brady maintained, of rather deep-water origin. The coarse conglomerate formed of volcanic pebbles at the base of the coral rock at Walu Bay confirms this view. I observed a large clam-shell (*Tridacna*) at the rifle butts at Walu Bay Quarry, and was shown large teeth of *Carcharodon* from this quarry by Sir Henry Barclay. Mr. Andrews has forwarded you a similar *Carcharodon* tooth. The evidence of these fossil sharks' teeth alone would prove the formation to be at least as old as Pliocene, while the occurrence of *Tridacna* shows that it is referable to the later rather than to the earlier Tertiaries.

4. Raised limestones. These are formed, according to Mr. Andrews' observations, only to a very limited extent of coral *in situ*, such as would have formed a true coral reef. True coral reef limestone was usually found forming a capping about one hundred feet in thickness at the top of the raised limestone. Such is the case in several places at Mango, and also at Tuvuthá, Thithia, and Kambara, etc.

Much of this limestone has been elevated from 800 feet to 1050 feet (Vatu Vara) above the sea. The base is usually not seen along the seaward faces of the islands, except in the case of Mba Vatu and Tuvuthá and Mango. At Mango there is a good section a short distance inland, showing the limestone resting on a foundation of marine calcareous rock with abundant fragments of decomposed basic or andesitic volcanic rocks, the highest level of the junction plane being about 400 feet above the sea. As no trace of this calcareous volcanic conglomerate can be seen in the sea-cliff less than half a mile distant, and about 400 feet high, it follows that the coral rock must thin out considerably against the inland foundation of the island, while it thickens rapidly seawards, as shown on Mr. Andrews' section.

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[1] American Jour. Sci., Vol. V., February, 1898. "The Islands and Coral Reefs of the Fiji Group." By Alexander Agassiz.

This, I think, points either to stable equilibrium of the earth's crust in that neighborhood for a sufficiently long period of time to have enabled the reef to grow out seawards on a rock formed partly of its own talus, partly of foraminifera and nullipores, or it points to upward growth of the reef during a slow subsidence. Mr. Andrews inclines to the former view. Had either elevation or subsidence, as the case may have been, taken place fairly rapidly and continuously, the result would probably have been the formation of merely a veneer of coral rock lying on the foundation rock.

It seems to be very difficult to obtain a reliable natural section showing the internal structure of this raised limestone, for two reasons: —

(i.) As the elevation progresses, the tendency is for each newer ring of coral and talus formed at successively lower levels to hide from view the base of the previously formed ring. See the description of Vatu Leile by Mr. Andrews. This masking of the older limestone formation by newer formations and thick soils is more conspicuous on the leeward side of the islands than on the windward, for while narrow terraces of coralline limestone, mostly now covered by deep soil, were added to the western side during the elevation of the atoll, not only was coral growth checked, but the sea even made some inroads into the earlier limestone rock, as proved by the wave-worn beach lines up to over fifty feet above sea-level.

(ii.) Chemical solution is constantly forming stalagmitic or tufaceous crusts over the cliff faces, sides of ravines, and even sides of caves in the limestone, and this material, of course, either hides the original rock from view, or by infiltration changes its original structure considerably. The limestones are much dolomitized in places, so that almost all original structure of the organisms composing them is obliterated.

5. Andesitic rocks, later than the raised limestones.

(*a*) Andesite and coral agglomerates. These are well developed at Mango. The inclusion of blocks of angular raised limestone, up to four or five feet in diameter, in this agglomerate proves that it is newer than the raised limestone, as Mr. Andrews is convinced that these included blocks belong to the raised limestone, and not to the older "bedded limestones," which latter are largely foraminiferal.

(*b*) Massive flows of andesite like those of Mount Rupert in Mango. These cap the coral agglomerates (*a*); they have a very fresh appearance, are in no places capped or encrusted by the raised limestone, and invest the raised limestone and enclose inliers of it. For these reasons Mr. Andrews considers these andesites newer than the preceding agglomerate and than the raised limestone.

These lavas rise in dome-shaped masses to a height of 700 feet above the sea, and attain a thickness of about 300 feet.

6. Basalts. These form small outcrops quite inconspicuous as compared with the andesites.

They are olivine basalts, having a very fresh appearance, and Mr. Andrews considers them to be of later origin than the andesites, and consequently the newest of the volcanic rocks of Fiji.

7. The present coral reefs. As regards the origin of the raised limestones of the Lau Group, it would, of course, be premature to advance any definite conclusions pending the examination of the collections made by yourselves and by Mr. Andrews.

At the same time, a brief statement might be made here as to Mr. Andrews' present opinion about them and my opinion as to their relation to the limestone penetrated to a depth of 1114 feet in the bore at Funafuti Atoll, Ellice Group. Such thin bands of the limestone rock from Lau as Mr. Andrews classes as true raised coral reef seem to me very closely allied to the bulk of the rock penetrated at Funafuti. Mr. Andrews concurs in this opinion. In the Lau Group, however, such true raised coral reefs proper, in Mr. Andrews' opinion, form only a very small proportion of the whole thickness of raised limestone. At Funafuti, however, they constitute by far the greater proportion of the whole thickness of rock proved in the bore. Whereas, then, at Funafuti, in my opinion, there is little calcareous rock that is not true reef, at Lau, in Mr. Andrews' opinion, there is little visible calcareous rock that is true reef. Mr. Andrews thinks that probably the raised limestones of Lau acquired their great thickness of over 800 feet by outgrowths of coral reef on a bank of coral talus and foraminiferal nullipore limestone during a long period of crustal quiescence followed by intermittent upheavals with several intervening periods of quiescence which led to the formation of the terraces.

Most of the raised limestone reefs of Lau are distinctly raised atolls, notably Tuvuthá, of which the old lagoon floor is about 350 to 400 feet now above sea-level and about 200 feet below the general level of its well-defined rim.

Terraced structure was certainly very plainly visible in a photograph by Mr. Andrews of Yathata.

In the case of Yathata, it is probable that whatever may be the age of its oldest and highest limestone area, whether it be late or middle Tertiary, it has representatives of limestones in its lower terraces of various intermediate ages between Tertiary and Recent, as these terraces are probably not terraces of erosion, but terraces of growth during pauses in the elevation.

That the latest elevatory movements have taken place in recent geological time, is proved by the freshness and good state of preservation of the wave-worn grooves in the sea cliffs at Vatu Leile and elsewhere up to a height of 50 feet above sea-level, as detailed by Mr. Andrews in his notes forwarded to you. Mr. Andrews' observations emphasize, I think, the need upon which you have so often insisted for making a separate study of each group of coral reefs and considering them in relation to the local geographical, biological, and geological conditions.

The whole question of the exact mode of origin of the massive raised limestones of Fiji appears to me to be one which can only be satisfactorily answered by careful examination of thin slices prepared for the microscope of your own collections, supplemented by those forwarded by Mr. Andrews.

SYDNEY, NEW SOUTH WALES,
March 15, 1899.

REPORT OF E. C. ANDREWS.

Introduction.

I LEFT Sydney, New South Wales, on Wednesday, June 1, 1898, arriving in Suva on the 10th of June. Some few days elapsed before I could get away from Suva for the Singatoka River, owing to the absence of suitable cutters. During that time I examined the area around Walu Bay, and searched the shore west of the islands of Lambiko of Vao for calcareous rocks while tools and requisites for blasting purposes were prepared.

A Tavua cutter was chartered through the kindness of Captains Calder and Woolley of Suva, and a rapid glance taken at the Singatoka River limestone, including also a visit to the famous dolomitic cliffs, thirty miles up the river. Returning from Singatoka to Suva, a Kandavu cutter was chartered for work in the Lau Group. While the cutter made the direct passage to Mango, I took passage in the S. S. "Maori" and a Taviuni cutter to the same island, calling and making rough notes en route on the islands of Ovalau and Taviuni. Arriving at Mango, we had to wait for the cutter, which occupied some fourteen days in the passage to windward.

Three weeks were taken up altogether in exploring Mango and examining its cliffs. From Mango our course was laid to Munia and to Loma Loma, and from thence we coasted along the eastern shore of Vanua Mbalavu with the intention of visiting Mba Vatu and Ngillangillah. Two weeks were spent in examination of the cliffs at this locality.

The section of North Ngillangillah being completed, we revisited Loma Loma and Munia and scaled the principal heights. Thence a dead beat was made to Tuvuthá and the ascent of that island effected, and then we continued on our way to Lakemba. The local cave was explored. We then steered for Kambara, and spent part of two days examining the same, and our course was laid to Totoya and hence to Vatu Leile via the Solo Light on Kandavu, where the raised coral reefs were examined. From Vatu Leile we made for Thuvu, and another visit was paid to the limestone cliffs, and a brief examination made of the recently upraised reef skirting the Thuvu-Singatoka sea-beach.

In this excursion I was accompanied and assisted by Mr. B. Sawyer, B.E., of Sydney University.

Afterwards I made short excursions to Mango, Vanua Mbalavu, Naitamba, Yathata, Vatu Vara, and Thithia to correct my first impressions of this limestone group.

I sailed from Suva on October 28, 1898, with the intention of obtaining samples of the Tongan limestone for comparison with the Fijian raised reefs.

I reached Sydney from Tonga via Auckland on the 17th of December, 1898. I wish to acknowledge here my sincere thanks to Prof. T. W. E. David of Sydney University for his valuable help and criticism; to Mr. B. Sawyer, B. E., of Sydney University, my associate in the Fiji expedition; to Captain D. Calder of the A. U. S. N. Co. for invaluable help in all matters of equipment; especially also to Dr. B. Corney for valuable hints and data; to Captain Woolley of Suva; to his Excellency, Sir G. M. O'Brien, Governor of Fiji; and to the Hon. W. L. Allardyce for permission to blast; to the Hon. J. M. Barron, owner of Mango, for his great hospitality; to Mr. J. N. Lennox, H. H. Steinmitz, Prince Ratu Lala, the Hon. J. Berry, Rev. J. Burns of Lakemba, and many others of the planters and settlers of Lau and the Singatoka River for their hospitality and help.

The present expedition was undertaken primarily, as detailed in your letter of instruction to me, with the idea of securing as many varieties of limestone as possible from the Fiji area; of selecting typical cliffs for sectional purposes, of collecting as many fossils as possible, of studying the topography and general geology of the Lau Group, and ascertaining if possible the basal limestone or volcanic rock supporting the more modern deposits, such as reefs. The extraordinary influences of erosion, the total lack of watercourse exposures except in caverns with walls concealed by long deposition from the roofs, the obscuring of cliff exposures by redeposition of calcareous matter in stalactitic form, the enormous amount of secondary calcite arising from solution of the corals, the dense vegetation, and the general absence of highways, all conspire to hinder good progress in geological researches in the Fiji Islands.

The means of transport in these, as in most of the South Sea Islands, is unsatisfactory. Many islands, of which Naitamba, Vatu Vara, and Yathata are types, are approachable only in tiny craft, and that also only in fine weather.

General Geological Structure.

THE LARGER ISLANDS.

Viti Levu.[1] — In this, the largest island in the Fiji Group, my researches were confined to an examination of the Suva district, of a ten-mile strip stretching from Nandronga Singatokawards, and a short excursion extending over some thirty miles up the large Singatoka River. Viti Levu and Vanua Levu stand out distinctly from all other members of the group, and bear the imprint of a hoary antiquity compared with the volcanic islands of Taviuni, Ngau, and Kandavu, as well as with the limestone islands constituting the Lau division of the Fiji area. Proceeding along the banks of the Singatoka River, interesting outcrops of limestone of high dip were observed. Volcanic agglomerates of porphyrite and masses of andesite rock, apparently identical with similar rocks in the younger islands, have burst through the more ancient sedimentary rocks. The volcanic rocks exhibit various stages of decomposition. The hills roll, cone after cone, behind each other to a height of 3000 feet, and the main road follows the curves of the lower hill shoulders, thus revealing numerous dykes, and thin beds of strata, dipping at high angle, which are crossed again and again in a few hours' walk. In places these strata contain a bright green cherty rock, interbedded with softer brownish layers.

The Stratified Rocks. — Argillaceous rocks and soft crumbling beds occur with high dip. They are brown in color and at times effervesce with acid.

The Dolomites. — These appear to underlie the strata just enumerated. They are principally centred in an immense block overlooking the river. They consist of two hills 1000 and 1500 feet respectively above the river, and reaching, in the case of the smaller one, into the water at the base. They are practically perpendicular, having a slope of 85° in places and 90° in others, and are uniformly hard and homogeneous in character from base to summit. They are tunnelled with caverns. To the eye or ordinary lens they are non-fossiliferous. Acid scarcely causes any effervescence. According to report this rock is found along a line roughly northwest and southeast, but I saw no trace of its development elsewhere.

Of the evidently later limestones that more or less fringe the shore of the island near the mouth of the Singatoka River, one notices, commencing with the older, a series of rocks which, excepting the oldest, conform to the same dip and strike. They comprise a vast group of limestones and so-called "Fiji soapstones" that form the nearer coastal scarps, reaching in places to a height of 330 feet above the sea. The oldest of these Singatoka rocks is a compact bedded blue and apparently non-fossiliferous limestone having a high dip (50°) (Plate **3**, Fig. 1). To this succeeds a series of soft rocks having an average dip of 15° (Plates **7**, **33**). The junction of this highly inclined blue limestone with the softer overlying strata could not be distinctly seen (Plate **32**). The next group of strata in ascending order is undoubtedly large and comprises a sandy species of limestone. This gives place to a shelly and foraminiferal zone; another series contains fossils of Pecten and other lamellibranch types, with here and there a stray, weathered, indeterminable coral (Plate **3**, Figs. 1, 2). Still another series comprises a dense, homogeneous, macroscopically non-fossiliferous zone, and this includes a six-foot belt of coral reef, containing Porites or Montipora. This, in turn, overlays a two-foot belt of red clay, and the top of the reef consists of a thin belt of finely laminated limestone. To this succeeds a great development in layers of a brown, friable rock that will scarcely bear the weight of the hammer (Plate **3**, Figs. 1, 2). A gap in the section occurs at this spot, due to drift sands of later origin hiding the underlying rock; but two or three miles toward Thuvu similar layers of fossiliferous limestone are again picked up, and in these occurs a belt of hard red limestone.

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[1] See A. Agassiz, Bull. Mus. Comp. Zoöl., 1899, Vol. XXXIII. p. 110.

At Thuvu the limestone has disappeared and its place is taken by hills 200 to 300 feet high of inclined "soapstone" (Plate **4**).

The series of friable and dense limestones just considered lies back about two miles from the sea, the Singatoka having deposited its enormous flat seawards in front of it so that the cliffs abut directly on it. On the seaward of the lower limestone formations and of the old Singatoka flat a modern elevation has exposed a reef wall in places as much as twenty to twenty-five feet above high-water mark (Plate **5**). This reef face is vertical.

"THE LAU GROUP" AND THE SMALLER ISLANDS.[1]

These may be divided for purposes of classification, as has been done before, into: The volcanic islands; The limestone islands; The volcanic and limestone islands.

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[1] See A. Agassiz, *l. c.*, p. 17.

The Volcanic Islands. — These include islands like Kandavu, Taviuni, Ngau, Nairai, Mbengha, Totoya, and Moala. Some of the islands, like Munia and Ovalau, are formed mainly of andesitic agglomerates (Plate 6) laid down rapidly in thick strata. In these beds occur layers of volcanic ash, finely comminuted, and filled with beautiful augite crystals. Generally this agglomerate consists of angular blocks so firmly welded in places as to render the junction of individual blocks almost indistinguishable. On Vanua Mbalavu layers of volcanic conglomerate occur with rounded pieces, and this as much as 500 feet above the sea. Again, as at Taviuni, on a large scale, and more or less on almost every island in the group, streams of lava occur, the so-called "vata loa" of the natives. On islands like Taviuni, Mango, Thithia, and Vanua Mbalavu, this vesicular lava appears so distinct as to seem but the product of yesterday (Plate 8). The basalt appears to have followed the andesite outbursts. Basaltic and andesitic rocks are seen everywhere on Taviuni and Mango. Taviuni contains numerous craters, one being nearly 3000 feet above the sea level, with its rim fully 4000 feet above the sea.

The Limestone Islands.[1] — These are very few in number and are small. Vatu Vara, Wangava, Wailangilala, Katavanga, and Namuka are the only ones I know to be wholly limestone. Fulanga, Karoni, and Aiwa I believe may be (in the Lau division) added to this list. The Yasawas are limestone, 800 feet high. With the exception of Fulanga, each of the above named is extremely small. They consist of compact limestones, very flinty in composition, and emitting showers of sparks when struck with a large hammer.

The Limestone and Volcanic Islands.[2] — These constitute a numerous and important group. Besides the two main islands, it comprises Mango, Vanua Mbalavu, Tuvuthá, Naiau, Lakemba, Kambara, Thithia, and Naitamba. These islands were, originally and generally considered, lands possessing and presenting as many as six or seven terraces or indications of elevation and subsequent reef extension. Subsequently came the upheaval which produced the volcanic agglomerates and lava masses. These burst through and destroyed a great part of the cliff slopes, and more or less filled the old inland lagoon areas. Such has been the case particularly with Mango, Thithia, Lakemba, and Vanua Mbalavu. At the latter island the force was so immense as to leave only the north and south extremities intact, carrying the middle reef formations as high as 500 and 700 feet above high-water mark, leaving but a miserable metamorphosed remnant to represent the pre-existent land now showing merely as chalcedonic blocks littering the razorback as it extends S-like on the surface of the sea.

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[1] See A. Agassiz, *l. c.*, p. 43.

[2] See A. Agassiz, *l. c.*, p. 88.

Basal rocks or basal limestones are of unfrequent occurrence. At Mba Vatu — the northern division of Vanua Mbalavu — huge stratified limestones occur as high as 250 to 300 feet above the sea. To the north of these dipping limestones the land is occupied by "terraced" formations, and to the south it abuts on a great andesitic massif. Fourteen miles south the coralline limestones lie unconformably on a bedded red laterite.

At Tuvuthá and Mango a very decomposed conglomerate or agglomerate of andesitic origin underlies a bright red limestone in the case of Mango and white limestone in the case of Tuvuthá. The cementing material is very calcareous. These rocks bear the stamp of great age, and have evidently a great development beneath the coral islands.

The Geological History and Topography.

The Main Islands.

The General Topography. — The topography of southwestern Viti Levu is characterized by numerous almost perfect cones, with smaller cones on their slopes.

In the Namosi, or central district of Viti Levu, sharp knife-like summits and aiguilles rise to 3000 and 4000 feet above the sea. These yield, on disintegration, fertile soils, especially in the valleys.

The great dolomites of the Singatoka River constitute a decided topographical feature. They rise almost perpendicularly with exceedingly large and sharp projections in the upper half, the result of long-continued erosion. From the base the strata rise straight as masonry for 400 or 500 feet; above that they become more or less broken. They appear to be exposed in part by the removal of softer overlying strata.

The Singatoka River itself has changed its course, and viewed from the huge tilted dolomites dominating the river, its old bed, now about 50 feet above the modern stream, constitutes a marked feature in the scenery.

Coastal Topography. — The coastal topography of the larger islands consists in the main of cliffs of elevated and shelly limestones of ancient date, scattered amongst huge rolling slopes of volcanic hills extending seaward. In these elevated shelly strata reefs of undoubted coral origin occur. These have cappings and bases of so-called "soapstone." This alternating structure is still more marked along the Tamavua River, near Suva, where many successive layers of soapstone and of limestone are visible in one exposure (Plate **39**). Terraces and beaches are not distinct topographical features of the larger islands, as they are in the members of the Lau Group.

With respect to the reefs surrounding the islands of the Fiji Group, we may notice that on the southwestern portion of Viti Levu the reefs are fringing.[1] Strange to say, the Singatoka River, large as it is (Plate **3**ᵃ) and bringing down a volume of fresh water comparable with that of the Rewa River, causes no sensible diminution of the fringing reef.

There is one small passage only, a very few yards in width, through which the escaping water at low tide pours out at the rate of six to nine miles per hour. Even this passage has a reef base nearly awash at low tide. For a distance of seventy miles towards Suva the fringing reef continues. But beyond this point, in a direction extending towards Ovalau, the reefs gradually recede for miles from the shore.

Vanua Levu is surrounded by an even greater mass of reef.[2]

TOPOGRAPHY OF THE SMALLER ISLANDS.

The islands of the Lau Group and such islands as Taviuni and Kandavu present the appearance of huge sloping lava flows as at Taviuni, as higher pitched slopes at Ngau, Nairai, and Vanua Mbalavu; or, again, as solid limestone masses rising from the sea. These mural fronts are roughly subcircular in shape, are some 400 or 500 feet high, and may exhibit vertical cliffs looking out upon large skirting sand flats, or, again, they may exhibit a slope suggestive of an inverted cup or truncated sugar-loaf. This shape is of general occurrence, its uniformity all over the group suggesting it to be the original slope of the reef before elevation.

Terrace structures and upraised lines of ancient sea erosion cut into the cliffs are also a frequent feature of Lau scenery. A detailed examination of Mango's topography and more or less complete notes on other islands visited is furnished here as a supplement to these general remarks.

Mango (Plates **1**, **2**, **9–17**). — This island is subcircular in shape, and as seen from the sea appears like a huge mass that has been upheaved about 500 feet above the level of the sea. The summit seems to be a vast flat broken in two places by great dome-structures rising above the general level, and almost equal in area to the base, owing to the wall-like front the island presents to the sea. The island is small, being eleven or twelve miles in circuit and three and a half miles in diameter. A strip of fertile flat about 100 yards in width runs round the greater part of its circumference and relieves the ruggedness of what would otherwise be an iron-bound coast. In one place this feature is found where the huge cliffs plunge abruptly into the water. Mango possesses a great number of vertical cliffs, some of them as high as 400 feet (Plate **9**), and where the limestone ring or girdle of the island persists, this cliff structure is varied only with the "sugar-loaf" formation.

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[1] A. Agassiz, *l. c.*, pp. 110, 118.

[2] A. Agassiz, *l. c.*, p. 121.

On a closer examination traces of a "terrace" up to 200 feet above high-water mark will be found on the northern and southern aspects of the island. Splendid patches of raised reef, with Porites and Astræan corals in abundance *in situ*, lie scattered over the sand flats and up the lower slopes of the cliffs. These are subsequent to the first upheaval.

The practised eye soon detects a want of uniformity in the limestone ring (Plates **12**, **15**, **16**, **17**). The wall structure is replaced by lava flows, and at the centre of flow the coralline rock is absent. Glancing along the line of cliffs from some point where they still preserve their original shape, the escarpment is seen to dwindle away towards the centre of flow of the disrupting lava, passing from great cliffs to insignificant wedge-shape, still preserving, however, the general level of the ring as it vanishes beneath the lava. Continuing the line of sight, the limestone is picked up again at the same level a little further on, now, however, merely a few limestone islands rising above the lava sheet. The volcanic mass pours through the gap made in the old limestone ring and spreads out, fan-shaped, away from the cliffs, carrying the island structure farther out to sea than formerly by some 400 yards (Plate **11**). This is the case on both the north and south of the island. On the northeast a vast natural break occurs in the old ring. This gap represents a former channel of communication between the outer sea and the central lagoon.

A coil of rope laid on the floor, sand poured gradually over any two opposite sides of the rope-ring till the cone-shaped sand masses rise considerably above the sub-level of the ring and hide the rope at that spot, a V-shaped gap cut in the rope at a spot bisecting either of the rope semicircles left, — this is the contour of Mango, with the rope substituted for the limestone girdle, the sand-cones for the andesite masses, and the V gap for the old passage from the sea to the central lagoon.

On the northeast of the island there is a small lagoon (Plate **12**) having a longer diameter of 1000 yards (Plate **1**) and a shorter one of 400 yards. A channel ten yards in width connects it with the sea through a narrow limestone belt, 50 to 100 feet high. There is a trace of an old reef on its margin.

A fringing reef of modern date with enclosed lagoons conforms in a general way to the shape of the land. These lagoons are deep holes, true lakes at low tide, some of them are fully nine fathoms deep. The floors are usually sandy, with scattered corals, while the steep walls of the lagoon are often formed of growing reef. The reef itself is much littered with huge blocks of coral débris, known locally as "nigger-heads" and "horse-heads." Other larger blocks occur, some of them 40 feet in height. They result from cliff ruptures, and have undercut bases (Plates **13**, **14**). In the deepest lagoon several small islands occur, partly volcanic, and partly limestone agglomerates lying in a cementing of andesite tuff.

Along the shores of the island "beach rock" is well developed, and at two or three spots along the shore streams of fresh water crop up between low and high water marks from beneath this beach-rock formation.

A rapid glance at the centre of the island reveals a limestone ring broken up by great volcanic outbursts of andesitic lava, dipping in most cases towards a great central depression (Plates **15–17**). The geometrical shape of this hollow is lost, owing to the intrusion of a vast andesite mass near its centre; from the sides and from the slopes of the lava streams forming the great amphitheatrical enclosure, vast alluvial masses have spread over the ancient limestone floor of the hollow. The old base or floor crops up now and again as a broken and weathered limestone, or as huge isolated limestone masses projecting above the alluvium or the lava slopes. At levels of 250 and 50 feet respectively above high-water mark, remnants of old reefs are encountered along the inland cliff exposures. The numerous caves of Mango are objects of interest. One of these occurs in a large bluff 600 or 700 yards inland. It is little more than a vertical hole 100 feet deep, with several minor lateral ramifications. Other large caverns gape on the coastal bluffs. They open out on the seaward faces of the cliffs in almost inaccessible positions. One or two penetrate the cliffs for distances exceeding 60 yards. In all these large subterranean passages the examination of the calcareous masses through which they have been formed is obscured from various causes. In one or two places, however, the limestone could be examined. Its general appearance was that of calcareous patches found on the modern reefs, containing no whole corals, but full of small fragments of reef organisms set in a fine, hard, compact white matrix.

Thithia (Plates **18-21**). — Thithia and Mango might be studied in detail with almost equal advantage. Whatever statement holds good in the description of Mango is equally applicable to Thithia. Thithia is a trifle larger, being fourteen miles in circuit and four miles in diameter. Both have the same vertical cliffs of limestone, the same forest-clad limestone slopes (Plates **18**, **20**, **21**), and the same uniformly inclined lava rock bursting to the sea. Mango is not so completely overwhelmed by volcanic material as the sister island, twenty miles away, and shows the limestone of the interior more nearly approximating to its former state than is the case with Thithia. Mango exhibits terrace formations and unmistakable signs of a very recent uplift, while at Thithia only traces of terraces can be detected. Formerly Thithia possessed an outer ring of raised coralline limestone origin, with a central hollow (Plate **19**). That hollow has been so encroached upon by lava outbursts that there is at present but a hint of its former extent. Thithia might now be described as a circular island, indented slightly at one end, and sloping steeply to the water, and with four or five bold black cliffs and forest-clad rocks to break the continuity of the volcanic slopes. These limestone rocks at times project but slightly through the down-like slopes of lava that have almost buried them. The development of rugged cliffs and isolated calcareous blocks comprising the broken country, heretofore mentioned, represents the survival of the old limestone perimeter (Plate **19**).

To the north are evidences of three platforms, respectively 400, 250, and 50 feet above tidal influence, the lower one being particularly well marked, with the middle one rising above it precipitously.

Nevertheless from this chaos we can restore the former condition of Thithia. It finds its parallel in Mango. Untouched in the volcanic uplift, the gap through which the ancient sea ebbed and flowed to the inner lagoon still exists (Plates **20**, **21**). Its 300 yards' wide entrance is protected on both sides by bold rocky scarps 400 feet high, and the whole line of gap may be traversed for nearly three quarters of a mile inland (Plate **20**), with no part more than four feet above high-water mark. At its head lie great boulders similar in appearance to those disposed along the modern shore lines of Lau. As with the modern shore rocks, so here at the terminus of this old sea-way (Plate **21**), their bases have been indented by the earlier sea at a former period. The whole locality has the aspect of a mangrove swamp left dry by the receding tide, and on a first visit to the place it is hard to disabuse oneself of the idea that here is a modern tide-affected area. Mr. J. N. Lennox, part owner of Thithia, assures me that there is no knowledge of the sea entering that gap.

The undercutting of cliff bases by sea-erosion is generally confined to limestone areas. At Thithia we have an instance where a volcanic agglomerate has undergone a similar carving by the action of waves.[1]

As with Mango, huge caverns occur, showing a great development of stalagmite and secondary calcareous incrustations covering the walls. The internal structure (15 yards in) reveals a rock similar in composition to the material of the general cliff face, containing very few corals, and is in hand specimens non-fossiliferous, as is the rule in the raised limestones of Fiji.

Vanua Mbalavu (Plate **22**). — This is literally "the long land." It is a distorted S shape. The belly and middle curves are composed of andesitic lava, andesite agglomerates, andesite basalts, and "talasinga," or burnt earth of the natives. This "talasinga" is a recognizable feature in almost any Fijian landscape. It is a soil arising from volcanic rock decomposition, and is of such a bright red that at times it is used as a pigment. The terminal points of the S consist of high bluffs of elevated limestone, reaching in the north, at Ngillangillah and Mba Vatu, a height of 500, and at the south a height of over 400 feet, at Malatta and Susui islands. The length of the main island is 15 miles, and disposed along the curving backbone of the island are the points of eruption which have so altered the former topography. At the south of the island the volcanic rock has tilted the limestone rocks.

Vanua Mbalavu, with its associated islands and islets, lies in a barrier reef of pronounced type (Plate **22**). A small patch of the lagoon separates the reef from the mainland to the west, while to the east it retreats for many miles from the land.

Naitamba (Plates **23**, **24**) lies 20 miles north of Vanua Mbalavu. It resembles Mango and Thithia in most particulars, but differs as to the extent of the volcanism. The northern extension of the old limestone ring now lies quite inland, owing to andesite extension at the base of the cliffs. To the south the cliffs have been fractured and lifted to a height of 600 feet above sea-level.

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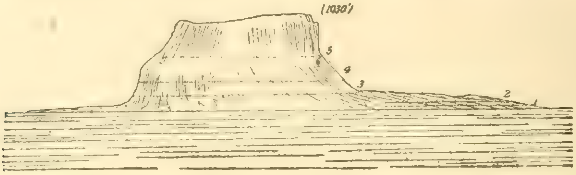
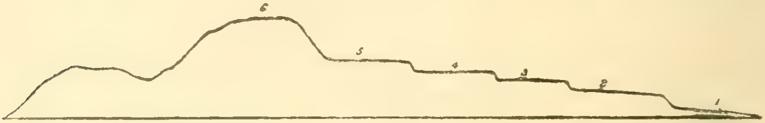
[1] See A. Agassiz, *l. c.*, Plates 62, 63.

Vatu Vara (Plates **25**, **26**). — The mass of the island rises as a vast truncated pyramid, presenting along the summit an almost perpendicular cliff 200 feet high. It possesses a sub-horizontal summit of some forty acres. On closer examination, the top is seen to contain innumerable pits and depressions, varying from 6 to 30 feet in depth. Traces of five uplifts are visible on its ascent. Three of these are "terrace" formations. Two are in form of beach-erosion lines.



VATU VARA SEEN FROM MANGO.

Yathata (Plate **27**). — Seen from the southeast, it looks like a hat. From the east it appears to consist of six steps arranged symmetrically with respect to a central dome. On the western side of the island this symmetry is broken by a volcanic mass that has welled up to the 500 feet level, scorching and whitening the limestone. A small island called Kaimbu is included in the same lagoon. They are 500 yards apart, and the water between is about 6 feet deep. On Kaimbu a line of beach erosion exists a few feet above high-water mark. The dominating cap, 840 feet in height, is "sugar-loaf."



YATHATA SEEN FROM NGILLANGILLAH.

YATHATA AND KAIMBU FROM MANGO.

Kambara. — It is much as Mango may have been, one solitary andesite mass of 30° slope, rising 470 feet above the sea to mark its era of active volcanism. This dome of lava[1] burst through the old cliff ring and carried the broken fragments up, subsequently, on the top of a rising lava.

Vatu Leile (Plates **28–31**). — This interesting island differs materially in many ways from the other Fiji islands. Topographically, it resembles the Vavau group, while lithologically it shows affinities with the Lau Islands.[2] The eastern coast is flat (Plate **29**), rising, like the northern shore of Tonga, but a couple of feet out of the reach of the high tides. As at Vavau, a deep deposit of soil covers the rocky base, and prevents geologizing to any extent. Through this flat long tongues of basalt have been protruded, reaching into the lagoon. On the western side are magnificent examples of former elevations. On a cliff face 100 feet in height (Plates **30, 31**), are no less than four well-preserved lines of beach erosion. These, with the modern one, constitute a marked feature in the landscape. They are, in cross section, like a quadrant of an ellipse with the longer semi-axis held horizontally. The most pronounced is that immediately above the modern line of beach erosion, and persisting for so many miles of such a height and flatness of floor as to have earned from the natives the name of "The Great Walk." The floor is 6 feet above high-water mark. It is 6 or 7 feet from floor to roof, and is eaten back into the cliff some 10 feet. The second is 14 feet, and the third and fourth are respectively 35 and 45 feet above the same datum line (high-water mark). It may be remarked, in passing, that a line of beach erosion corresponds to a terrace on the opposite side of the island. But it must not be forgotten that these evidences of erosion do not stretch as geometrical lines throughout the length of the western cliffs. Only in one favored spot can the four be seen at once. On the main cliff the third and fourth lines are very faint, while the second is invisible.

Corresponding to "The Great Walk" (Plate **31**) is an upraised reef spreading out from the cliffs, which at this spot have retreated slightly inland. The reef is bounded to the rear by a cliff 100 feet high and by the upper part of "The Great Walk." This flat is about 6 feet above the tides. So recent is the uplift that hundreds of loose corals lie over the platform. The platform itself consists of reef-débris rock, as hard and dense as any Lau limestone, while here and there scattered coral are stuck in it like stray pins in a cushion.

By walking behind the sea-cliff, another set of rocks about 50 yards inland is observed, and here at the same level, 6 feet above high-water mark, occurs the raised reef with scattered corals and the line of beach erosion. The traces of a raised sea-beach from 7 to 11 feet above the present tidal limit are still fresh at their feet. These inland cliffs rise some 30 or 40 feet above the flat and are encrusted with coral reef formations. At 16 feet above high-water mark a small patch of disintegrated raised "beach rock" may be seen.

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[1] See A. Agassiz, *l. c.*, Plate 78.

[2] A. Agassiz, *l. c.*, Plate 100.

At Thuvu, as at Vatu Leile, the dead corals litter the reef and project above its surface. It seems to have a general level of 6 to 8 feet above the tide, with a higher development to the rear, rising from 16 to 20 feet. Traces of a more elevated beach (25 feet) also occur (Plates **30**, **31**). The reef has grown on the older inclined limestones.

Wangava. — It has rugged slopes rising steeply (50° to 60°) from base to summit, to a general level of 300 to 350 feet above the sea. Half-way up the slopes traces of a "terrace" may be seen. The centre of the island is depressed, containing a lake which rises and falls with the tide, as I am informed by Hon. W. L. Allardyce. (A similar case occurs at Nomuka, in the Tongan Group.)

Taviuni (Plate **8**). — It is of blunted wedge-shape, and its axis, determined mostly by volcanic cones and craters, lies approximately north-northeast and south-southwest. As seen from the south, it is cone shaped. An examination of the western slopes reveals flows of basaltic lava partially hiding masses of older lava flows of steeper slope. To the east it falls precipitously, and the later basalt does not appear to have influenced the topographical features of this division of the island.

An inland lake occurs at the 2800 feet level. It is either contained in an extinct crater or has been formed by the closing in of dome-shaped masses on one another. A curious feature in this old lake is the repeated occurrence of long narrow belts of water running in all directions through the bog. Their edges are sharply defined by the transparency of the water when contrasted with the surrounding bog.

Ovalau (Plate **6**). — One of the most rugged and picturesque islands of the group. It is contained wholly within the Viti Levu barrier. It is 2100 feet in height, and is composed of huge beds of evenly dipping strata carved into deep valleys, aiguilles, cliffs, and dome-shaped masses. These strata are andesite agglomerates, in places consisting of augite-andesite blocks loosely aggregated, in others of angular blocks firmly welded together, and again beds of andesite ash occur full of augite crystals.

Munia. — It is described most accurately by calling it "a miniature Ovalau." The same rugged cliffs of andesite agglomerate occur on a smaller scale, the total height here being 1000 feet.

Lakemba. — The mass of the island is composed of andesite hills, crowding thickly one upon the other and rising at the highest point to 720 feet above high-water mark. The former state of the island is represented by a mere fringe of coralline limestone on the southwestern extension of the volcanic mass. The whole configuration of the older limestone has been altered, unless, indeed, Lakemba was at one time an extensive limestone island. A little bigger volcanic display, and not a vestige of the older limestone would have remained, except perhaps as blocks in andesite ash beds, as is the case with some of the Mango limestones.

The great attraction of Lakemba is its cave, piercing the fragment of limestone that skirt the volcanic slopes. The white residents describe it as an immense tunnel, easy of examination, and running for about two miles through the hill. Measurements by myself reduce this great length to 500 yards. Even thus the statement is misleading, for the cave disappears in the hill, describes an arc of a circle, and by so doing reappears round the corner of the same bluff that it started at. From entrance to exit is about 200 yards measured round the outside of the cliff, and the exit is 100 feet above the entrance. The cave is more easily explored than any I have visited, the floor being fairly smooth, wide, and of even slope. Generally the roof is about 50 feet above the floor. The walls, where clean, reveal the structure of a raised reef, composed of corals and fragments of mollusca.

Lines of Beach Erosion. — These may be divided into two groups, the ancient and the modern lines of tidal wear.

In the islands of the Lau Group, and confined almost exclusively to the limestone formations, the effects of recent beach erosion are very pronounced.[1] When a group of islands, of which the hundred isles of Ngillangillah (Plates **22**, **35**) and Mba Vatu may be cited as illustrations, have their windward face overlooking a fairly deep lagoon or are placed directly opposite an opening like the Ngillangillah Passage, we find small islands quite undermined by wave agency, while others project in mushroom form above the surface of the lagoon (Plate **35**). On the windward side of the Ngillangillah Group the erosive action has extended as much as 8 to 10 feet vertically and into the cliff face from 14 to 15 feet.[1] To the leeward this cutting into the cliff rarely exceeded 4 feet vertically or laterally. Other islands furnish equally good examples of this modern erosion, but only in cases where the cliffs faced a wide expanse of lagoon or sea, with no intermediate reef.[1] South of Thithia a remarkable mass of volcanic agglomerate occurs that exhibits similar weathering, inducing thereby a toadstool shape in the block.[2] Fine erosion effects are visible on the great outlines of the Mango cliffs, which have been carved into the most bizarre possible forms. Equally curious also are some of the under-cut cliff-bases at Fulanga,[3] where islands filling the lagoon of the raised reef exhibit every stage in this undermining of the cliffs. Besides the islands just enumerated, Vatu Leile,[4] Naitamba, and Kambara show equally striking results due to erosion. In some cases the redeposition of carbonate of lime has taken place to such an extent as to almost obliterate the traces of the erosion-line (Plates 28, 30, 31). Much iron as ferric oxide is mixed with the redeposited lime material, and imparts a rich-brown or red color to the mass.

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[1] See A. Agassiz, *l. c.*, Plates 73, 74, 92, 93.

At Vatu Leile this redeposition of calcareous material charged with ferric oxide has gone on very largely in the line of erosion known as "The Great Walk," parts of which it has completely obliterated, while other parts are half filled with large masses of the deposit. At the southern extremity of Vanua Mbalavu, another line of beach erosion occurs tilted at 15° to the horizon. Here again the cliff has almost regained its original shape by subsequent refilling of the wave-worn groove.

Most of the islands, as Thithia, Lakemba, Taviuni, Vanua Mbalavu, Vatu Vara, Kambara, and Vatu Leile, have more or less well developed flats extending along the bases of the hills, whether volcanic or limestone. The Mango flats vary from 100 to 250 yards in width, and throughout this extent are fairly level. They are most persistent along the windward or southern side. Two flats were examined, one on the south and one on the northeast of the island. In both cases they lay at the bases of limestone cliffs 400 and 500 feet in height. The seaward edge of the flats is perhaps higher than the middle portion. To make sure of the origin of this raised portion, two holes were sunk till the harder basal rock was reached. In both cases the old beach rock was found, and this at a distance of nearly 200 yards back from the present similar formation.

[1] See A. Agassiz, *l. c.*, Plate 94 (Ongea).

[2] See A. Agassiz, *l. c.*, Plate 62.

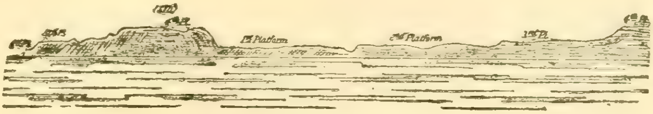
[3] See A. Agassiz, *l. c.*, Plates 82, 83, 84.

[4] See A. Agassiz, *l. c.*, Plates 96, 100. 102.

It would thus appear that some of the flats are wind-blown formations, and not the results of recent upheaval, as in the case of Lakemba, Thithia, and Vatu Leile. [The reef-flats are due to submarine erosion. — A. Agassiz.]

Elevations of the Fiji Group. — From the consideration of the raised coralline limestone alone, it is clear that a greater elevation may be claimed for the northern division of the Fiji Group than for the southern one.[1] The Yasawas (800 feet), Thikombia-i-ra (630 feet), Tuvuthá (800 feet), Vatu Vara (1050 feet), and Yathata (840 feet), are lofty heights compared with the elevated islands stretching to the south of terraced Tuvuthá. The elevations decrease in altitude as we leave Tuvuthá and retreat from the equator. At 18° south latitude, we have Naiau with 580 feet, at 19° south latitude Kambara and Wangava from 300 to 350 feet, and still farther south Fulanga with 260 feet of uplift. Thus it seems that the great uplift or series of uplifts reached its maximum on or about the 17th parallel of south latitude. Whether this uplift was due to one elevating influence, as suggested by J. Stanley Gardiner,[2] or due to intermittent periods of uplifts and repose, is now to be considered.

Number of Elevations. — As mentioned before, Mr. Gardiner considered the probability of one uplift for Lau. In this he was influenced by the apparent lack of visible "terrace" or even incipient "terrace formations," and from the repeated occurrence of huge vertical cliffs noted by him in his researches conducted in the Lau Group. But the evidence for repeated uplifts in place of a rapid and single rise seems incontestable when read in the light of the following facts.



MBA VATU FROM MANGO.

Appended is a summary of the numbers of indications of upheaval in individual islands, and from a careful study of the first 50 feet of Vatu Leile, Vatu Vara, and Yathata, it seems probable that many former traces of elevation have been completely obliterated, due to the subsequent degradation of the limestone,[1] and the actual upward movements outnumber those which can be observed.

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[1] A. Agassiz, *l. c.*, p. 131.

[2] Proc. Camb. Phil. Soc., 1898, Vol. IX. Part VIII.

Ngillangillah,	3 (4 ?).	Mba Vatu,	5.
Mango,	2.	Thithia,	3.
Ovalau,	1.	Yathata,	7.
Vatu Vara,	4 (5 ?).	Tuvuthá,	4. Plate **3**, Fig. 3.
Naiau,	2.	Lakemba,	2.
Wangava,	2.	Kambara,	2.
Vatu Leile,	5. Plate 30.		

Of all the elevations the trace of the last upheaval is specially well preserved in several of the islands. Speaking very generally, it occurs approximately at the same height above high-water mark in the group.

At Ovalau an old reef is exposed in a small creek at the back of the main hotel. This watercourse has cut through a loosely aggregated mass of andesite blocks and pebbles, several feet in thickness, and now runs along a coral floor exposed by its own erosive and denuding action. This raised coral floor is almost indistinguishable from the modern reef-flat. The highest tides do not quite cover it.

At Vatu Leile the evidence of a recent uplift is undeniable. It can be seen on the eastern edge of the island in the form of a flat removed but a few feet from the reach of the tides (Plate **29**). On the west it takes the form of an enormous groove extending for miles, flat underfoot and arched overhead (Plates **28**, **31**). At Yathata we have the same evidence as at Vatu Leile, and at Lakemba we have an extensive flat stretching along the south of the island and reaching from the present reef inland as far as the foot of the volcanic slopes (Plate **34**).

If we consider the vertical cliffs of Lau as the original steep submarine slopes rather than due to sub-aerial and beach erosion subsequent to their upheaval, then it seems reasonable to accept a much smaller loss to the islands by erosion than a first glance would appear to justify. Some of the islands are known to consist of limestone masses topped by sub-horizontal caps. The terraces, again, of the older cliffs appear from certain points as perfect level plains (Thithia, Tuvuthá, Yathata), and the truncated cone structures of some island masses suggests the contour of the original reef.

If we admit the persistence in the general level of such raised platforms as Tuvuthá, Vatu Vara, and Yathata, and of the original slope of the raised reefs, then the amount of loss by erosion seems confined to such pits and cracks as are seen on the summit of Vatu Vara, which although in places 30 and 40 feet deep, have not altered materially the original contour of the summit.[1]

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[1] A. Agassiz, *l. c.*, pp. 58, 78.

Observations taken in the Windward Isles of the Group show a remarkable similarity in this slope. Many of the angles of inclination to the horizon of the limestone bluffs averaged 50° to 55°, with a final 100 feet of steeper slope. This top part might go even higher than 75°. The truncated "sugar-loafs" are a topographical feature perfectly unmistakable (Plate 27).

On examining these slopes closely, they are found to consist of blackened and weathered needle-like formations. The minute ridge-structure mentioned before is developed to such a degree as to render climbing up the steep faces dangerous, owing to their being so worn away as to yield to the slightest touch in places.[2] Struck with a hammer, these eroded blocks, of perhaps five hundredweight, and attached to the rock mass by a column only one or two inches in diameter, ring like bells, and a very slight blow is often quite sufficient to send them crashing down the hill to the débris heap below. Notwithstanding this weathering, the remainder still marvellously preserves the original contour of the reef as it rose from the waters.[3]

At the base of these escarpments great talus heaps accumulate. These were formed, apparently, in many cases, under submarine conditions. The base assumes a less highly pitched angle of slope than the upper development. Furthermore, denuded of its débris covering, the basal rock, projecting here and there in rocky ribs, possesses a less slope than the upper part.

Again, the angle of inclination may exceed 80°. Then the cliff varies altogether. It is no longer black, but more commonly assumes a yellowish-white or brown color, and the face is encrusted with secondary calcareous material. This veiling of the cliff face hides otherwise easily determinable characteristics of the limestone. Some few of these perpendicular exposures are most likely due to rupture subsequent to upheaval. But this is exceptional. At the north of Mango are three cliffs (Plate 9) close together, 300 feet above the talus, and so conspicuous as to constitute landmarks far out to sea. At the base of one of these lies an immense block 100 feet long and some 30 feet thick. This is a recent fall, while all around and below it are thousands of blocks with isolated specimens as much as 100 tons weight. At Thithia there is an exposure of limestone preserving a beautiful slope of from 50° to 60° for a couple of miles. In one place, however, this continuity is broken. A huge block of some 20,000 tons (150 × 50 × 60 feet) has slipped down slightly, and should it fall over would expose a cliff over 100 feet in height. The precipices occupying the upper 300 feet of Vatu Vara may have been formed similarly.

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[1] For a statement of the opposite view see A. Agassiz, *l. c.*, p. 74, and Am. Jour. Sci., Jan., 1900, p. 42; *ib.* Feb., p. 110; *ib.* March, p. 196; *ib.* May, p. 372.

[2] See A. Agassiz, *l. c.*, Plates 97, 98.

[3] I think Mr. Andrews is mistaken. The immense amount of denudation which has taken place in the Fiji Islands and other elevated reef islands in the Pacific I have examined shows that the original reef slope is not preserved to any extent. It has usually been greatly obliterated by denudation and erosion. — A. AGASSIZ.

Perhaps, however, the majority of cliffs represent originally steep submarine slopes. Again, on the western side of Vatu Leile the cliffs, 100 feet in height, persist for miles and are quite vertical (Plates **28**, **30**, **31**). Yet on these cliffs are to be found no less than four well-defined lines of old beach-erosion. Therefore these cliffs must have been submarine. There has, however, been a certain period of quiescence since the last uplift, for a modern fringing reef has formed outside of the cliffs. The next uplift would give a terrace structure to Vatu Leile. Similar evidence is given from Yathata and Vatu Vara (Plates **25**, **27**). In many cases there are no outliers indicating an erosion so long continued as to eat back the "sugar-loaves" into enormous 400 feet cliffs and to have got rid of the vast accumulations of débris that would result from such a dismantlement of the gigantic vertical exposures. For it must not be forgotten that many high cliffs gather comparatively little limestone débris at their feet. In some instances the cliffs abut directly onto a sand flat with no intervening talus to lessen the angle of ascent.

The Nature, Origin, and Age of the Elevated Limestones.

Tuvuthá (Plate **3**, Figs. 3, 4) furnishes positive evidence of four elevations as terraces, occurring every 200 feet. Yathata is equally characterized by its terraced appearance. Vatu Vara presents steep acclivities and very poorly developed terraces. Vatu Leile emphasizes the short and frequent intermittent uplift, while Mango, Kambara, Mba Vatu point to long-protracted periods of stable equilibrium.

Of all the islands in the Lau Group, none perhaps are more remarkable than Tuvuthá, Vatu Vara, and Yathata. They are closely allied in structure, as regards height and traces of elevations. Tuvuthá is, perhaps, the most remarkable of all. Its summit is represented by a curious peak (Plate **3**, Figs. 3, 4), 800 feet above the sea, and rising 150 feet above the rest of the island. This mass consists of a compact coralline limestone, fairly horizontal, though eroded into pits and cracks. This cap is of several acres' extent only. The sides are steep. On the sea-side it presents a steep declivity to the water. It rests on the rim of the central hollow some two miles in diameter. This, the second "platform," is merely a thin coralline rim dipping sharply towards an inland crateriform cavity, some 250 feet below the level of the "platform." The floor consists of weathered limestone, and is densely wooded. At one end a gap occurs through which the material of the once continuous platform appears to have been passed out in solution. Below this again is another platform or terrace, also well marked (Plate **3**, Figs. 3, 4).

Vatu Vara has been described before. It is mentioned here again merely to emphasize its height (Plate **25**), its terraces and sea-erosion at the 800 feet, 600 to 700 feet, 350 feet, 25 and 15 feet levels.

Yathata is similar to Vatu Vara, especially in its sub-level cap (Plate **27**) of several acres only and its well-defined steps or terraces here. Another interesting point at Yathata is the comparative thinness of the coral rock.

Mba Vatu and *Ngillangillah* appear from the deck of a boat to consist of huge coralline masses either as coral reef or reef débris (Plate **35**). This would give them a thickness of coral growth amounting to at least 500 feet. By searching, however, an exposure was discovered of a beautifully bedded limestone underlying the coralline rock. These strata consisted of compact brown and yellow stone, apparently non-fossiliferous, and reaching up through the mass to a height of nearly 300 feet. This may occur as a base for the whole mass of Mba Vatu, but the coral growths have seized upon it as it approached the surface, and terraces have spread out from it, thus hiding it from view. The cliff of bedded limestone stands out boldly amidst its coralline surroundings, and appears to owe its exposure to-day to some past cliff rupture whereby the encrusting coral growths were separated from the stratified rock. Three miles away, and on the other side of the island, similar beds occur, but now they are but 50 feet in height and have very little coral growth attached to them. So that on this block 500 feet in height there is at most not more than 200 feet of coral growth.

Malatta. — To the south of Vanua Mbalavu, and 14 miles from Mba Vatu, a small patch of limestone, about 100 feet in height, has escaped the general disruption of the limestone by the volcanism. Here an old line of beach erosion is found, tilted at 15° to the horizon, and almost obscured by abundant redeposition of calcareous matter charged with ferric oxide. A small hole exists near the present sea-level in the limestone, and by crawling in one finds a small cave about 8 feet long and 3 feet wide. The sides are composed of red volcanic clay most distinctly bedded. Above this is found a reddish, hard limestone, and a very short distance away the coral rock itself occurs. Hot springs also exist throughout this limestone area.

Mango. — On the summit of a typically shaped andesite dome, and carried to its present position by the eruption of this same lava mass, a massive bedded limestone occurs (Plate 2, Fig. 1). It overlays a greatly decomposed volcanic conglomerate, gray to greenish in color. A number of gasteropods are scattered throughout the mass of the conglomerate. The stratified beds immediately above the decayed volcanic material are a dense, compact, reddish limestone, with fragments of fossils in places. It is very similar to the basal limestone at Mba Vatu and Malatta.

The bulk of this volcanic conglomerate cannot lie at a depth much below sea-level, if, as seems probable, its thickness is comparable with that of the outlier shown on the left hand of the section of Mango given on Plate 2, Fig. 1, which has been pushed up into its present position by an outburst of andesite.[1] We can easily avoid the necessity for explaining away huge deposits of coral reef origin, since the overlying reef material occupied but a fairly thin crust.

Tuvuthá is as instructive as Mango. An old volcanic conglomerate almost identical in appearance with that seen on Mango occurs on the sea beach. A newer andesite lava has broken through and poured over it and also towards the limestone cliffs, leaving a gap between the two.

Geological History of the Lau Group and its relations to the Western Fiji Islands.

It is now possible to suggest the general lines along which the present features of Lau were developed. Calcareous deposits, which afterwards formed the "bedded" limestones, were laid down on the floor of the ocean, the submarine plain which later was to form the foundation of the Lau Group. The existence of a basal volcanic conglomerate below the reef rock at Mango and Tuvuthá shows that there succeeded a period of volcanism, probably in Tertiary time, during which masses of volcanic material were heaped up along a fairly well-marked north and south line of weakness. The highest of these masses of volcanic rock, such as Yathata, Tuvuthá, and Vatu Vara, came within the reef-building zone of corals, and reefs commenced to form upon them. Alternating epochs of upheaval and stable equilibrium followed, during which the reefs grew outwards over calcareous banks as well as the bedded limestone. This is demonstrated by the long lines of erosion cut into the cliffs of Lau and the sub-horizontal terraces above them. This state of unrest must have continued, for a long period of time, to have produced the vast masses of limestone like those of Mango and Tuvuthá.

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[1] This does not imply that compact basal limestones project above the floor of the central hollow, but that the undisturbed and the disrupted rock are similar in their upper portions.

Another volcanic phase occurred in recent time. The andesite outbursts, which disrupted the old reef rock and bedded limestones, formed the coarse agglomerates with large included lumps of coral, and capped the latter with domes of lava. Many of the limestone islands became centres of eruption. At first numerous explosion craters were formed, and blocks of andesite and reef limestone were hurled from the vents until large islands were piled up by the ejectamenta. The former island of Vanua Mbalavu was almost completely wrecked as a result of the volcanic explosions.

Another instructive feature in these outbursts is the fact that the bases of the great limestone cliffs became in many places the centres of disturbance. If the eruption was extensive, then the cliff vanished and a heap of calcareous agglomerate was all that was left to attest to its former existence. If the disturbance was smaller, then the volcanic matter welled up from the cliff base without wholesale fracturing of the limestone.

Subsequent to, or perhaps immediately after the first paroxysmal outbursts, the andesites welled up in dome-shaped form and buried the coral agglomerates, produced by the earlier explosions, as well as the surrounding limestone. A final phase in the eruptions is marked by the later eruptions of olivine basalts. These found vents at the bases of the older andesite domes, and at Mango are represented by small tongue-shaped flows and minor masses.

From these fragmentary traces of basal rocks and from these indubitable signs of elevation, it is possible to understand the mode of formation of the Lau limestones and their subsequent elevation. Along the submarine plateau and running a little west and east of a meridional line, volcanic masses were erupted along the axis of regional elevation; and on these as a base great accumulations of volcanic ash and conglomerates were deposited, mixed with accretions derived from the tests of animals provided with calcareous shells; or again great stratified limestone deposits were found which are comparable to the compact limestone strata of the Singatoka area (Plate **3**, Figs. 1 and 2), and which, like them, may be non-fossiliferous, while others again may contain scattered corals and shells; and that these bedded rocks came within the reef-building zone, either by uplifts like those traced to-day on the Vatu Leile and Vatu Vara cliffs; or by their own increase in thickness during a period of stable equilibrium; or again by the joint results of elevation and accretion. Much of the limestone mass shown in the sections of Mango and Tuvuthá[1] (Plates **2** and **3**, Figs. 3 and 4) is doubtless (in its lower part) composed of compact bedded limestone.

After the first period of elevation succeeded periods of rest, during which such masses as the second "terrace" of Yathata and Tuvuthá were formed. While Yathata, Tuvuthá, and other islands show broad flat land at this stage, Vatu Vara shows but an incipient "terrace" structure. This might be accounted for if Vatu Vara was building on a very steep slope. In this case the corals could advance but slowly on their own talus, while if the other islands had broad flat patches of land to build on, or craters, they could easily assume their present great extension at this level.

From the next point of upheaval (the 400 feet level) to the present sea-level, the evidence points to smaller upheavals, with intervening periods of protracted rest. One of these periods of rest was of much longer duration than the others, and marks the 250 to 300 feet level.

THE METAMORPHISM OF THE LIMESTONES.

The limestones near Suva are generally interstratified with the "Fiji soapstone," and this is especially noticeable in the wedge-shaped mass at Walu Bay. This superimposing of the "soapstones" upon the calcareous rocks has suggested[2] the possibility of the induration of the limestones of Lau by exposure and water soakage, and that the immunity of the Suva limestones from this metamorphism is due to the impervious character of the "soapstone" cap. Even a cursory examination of the Singatoka River area, where limestone occurs in all varieties of hardness and compactness, shows this not to be the case. There we have an escarpment

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[1] The volcanic peak drawn as the base of the summit of Tuvuthá, Plate 3, Figs. 3, 4, is merely provisional, as there is no direct evidence of its being such.

[2] J. Stanley Gardiner. The Coral Reefs of Funafuti, Rotuma, and Fiji. Proc. of the Camb. Philos. Society. 1898.

(Plate 7) more than a mile in length and exceeding a height of 300 feet, the rock is stratified, and dips at a uniform angle of 15°, so that as the surface of the ground is nearly level, each individual bed crops out at the surface. One series of beds comprise layers of loosely compacted calcareous sand; others again are as hard as marble. The rocks are very similar to those at Suva. At the Singatoka, however, there is no trace of soapstone nearer than Thuvu, several miles away. There is no non-porous capping to the Singatoka bedded limestones.

The induration, therefore, of the raised reef limestones appears to have been quite independent of the presence of an impervious overlying rock such as "soapstone."

In the Lau area, the metamorphism of soft coral into hard dense rock is emphasized as strongly at the sea-level as on the island summits. The recently elevated Vatu Leile reef-flat, the latter some 6 feet above high-water mark, although strewn with hard corals, is hard and flinty as any limestone observable anywhere. This statement must not be considered to have universal application. This hardening extends only to the greater part of the reef-flat, — that part composed only of reef-débris, — and not the real coral masses representing a former belt or patch of growing reef. The raised coral masses found in the lower cliffs of Mango, Ngillangillah, Kambara, and Vatu Leile, although possessing an exceedingly hard shell ringing and emitting sparks under the hammer, were nevertheless soft and cellular within. So soft is the portion beneath this hard exterior that individual corals may be crushed beneath the fingers. At the same level, however, rock not formed of a coral mass is generally solid throughout.

This can be seen in a less degree on the "Liku" or cliff coast of the Tongan Group. There whole cliffs of crumbling material, similar to those observed at Singatoka (Plate 38), are exposed to the rollers of the Pacific. All along the coast of Vavau great masses of rock are perpetually falling and revealing a whole harvest of corals and shells more or less indurated or changed to translucent calcite, and lying in a soft white matrix. But where the cliff has preserved its integrity and still shows the original slope of the reef seawards (Plate 36), there a hard crust of limestone protects the soft interior. This is also observable on the fallen masses, the resulting débris of the soft coral cliff.

On the raised limestones of the Thuvu-Singatoka area a reef has grown, which has since been elevated. While the greater part of this reef mass is dense and hard as the Lau stone, the older basal rocks are still soft as those of the Walu Bay area.

The rock of the second, third, and higher elevations has generally undergone alteration (induration) to a depth of which the limit cannot be ascertained by blasting, and this induration has been more extensive than that which has affected the lower and newer limestones, and has spread through the coral reefs proper as well as through their associated coral débris. At the 300 feet level on the sides of Ngillangillah, an elevated reef mass 50 feet thick and consisting of corals, such as Porites and Montipora, shows that the pores of the corals have been almost wholly obliterated through solution and secondary addition of lime. At the higher levels on Kambara, the coral structures have changed to calcite in many places, and lie in a crumbling calcareous base. But in most cases all coral structure has vanished, the spaces formerly occupied by the corals being represented by dome-shaped cavities (Plate **37**).

At Vatu Vara a white dolomitic rock is filling the pores of the corals, and they are gradually disappearing. This dolomitization is seen at different levels in the Lau islands. Thus at Mango, 240 feet above high-water mark, numerous patches of white rock are found which hardly effervesce with acid. The dolomitization observable on the slopes of Vatu Vara is most pronounced, and its mode of occurrence suggests that it took place from the cause above mentioned during long pauses in the elevating movement; but the apparent absence of such dolomite patches in the present lines of beach erosion is opposed to the supposition of the coincidence of dolomite belts with old beach lines, as the same dolomite may have resulted from the absorption by the limestone of magnesium salts from sea-spray.

Another factor in rock alteration is the development of calcite along the higher levels. This may take the form of banded, colored calcite, filling large gaps, which is so common a feature in the older rocks of Mango, or it may take the form of transparent rhombohedra, about one inch in diameter. On the old, undisturbed raised reef flats, numerous patches of this calc-spar formation may be noticed. They are very common on the sub-level summit of Mba Vatu. They occur at Mango less frequently, while in Naitamba we find the finest calcite crystals; they frequently exhibit a radial disposition, and occur in numerous patches, and are almost invariably connected with old reef flats or lagoon areas.

From the foregoing considerations, it seems reasonable to infer that the agents which produced the hardened shell of the lower limestone cliffs of Lau and those which formed the secondary ferruginous calcareous rock of the beach-erosion levels and compacted the "beach rock," are similar if not identical; and these, together with the more pronounced dolomitization at the bases of the old terraces, appear to make up the sum of the more conspicuous metamorphic phenomena at work in the limestones of Lau.

The Volcanism of Fiji with reference to Lau and the Smaller Islands.

The erupted material of Viti Levu appears to consist of andesites, porphyrites, and andesite tuffs. At Suva great beds of volcanic boulders occur beneath the reef limestone, intercalated in the "soapstone" at Walu Bay. Some of the rounded blocks are upwards of 15 inches in diameter, and are surrounded, in individual cases, by a thick layer of soft-brown earthy crust, the result of the rock decomposition. They consist of porphyrite, quartz, and felspar porphyry, andesite dolerites, and andesites. As the base of the quartz and felspar porphyry is minutely sphenelitic, the rock probably represents an old rhyolite flow.

In the smaller islands the prevailing rock-types are andesites, occurring as lava and agglomerate and basalts, the latter occupying a much smaller area than the former. The influence of the volcanism on island-making will be appreciated when it is stated that Taviuni, Kandavu, Ovalau, Ngau, Nairai, Totoya, Moala, and Matuku are wholly volcanic, while islands which to a casual observer seem wholly limestone, such as Mango, Thithia, Vanua Mbalavu, and Naitamba, are two thirds volcanic, only the remaining third being limestone. Vanua Mbalavu affords splendid examples of andesite agglomerates and conglomerates covered with andesite lava, and exhibits numerous small outlying islands formed of andesite tuffs covered with lava and pierced with dykes of the same material.

Ovalau, Munia, and Vanua Mbalavu are, in great part, composed of huge, uniformly dipping strata of andesite blocks (Plate 6). These blocks are angular, and present stages of coarseness varying from the finest grained rock with a few scattered pyroxene and plagioclase crystals to blocks consisting of huge idiomorphic crystals of augite and felspar crowded in a fine base.

Insular masses, such as Ovalau and Munia, composed of andesite agglomerates, present very high angles of slope to the sea. In fact, the coastal scarps can hardly be described as slopes. They are very steep ascents broken by precipices 400 or 500 feet, sheer in places. The soft ash beds throughout the mass allow weathering into gorges and cliffs to take place very rapidly. The slopes of andesite flows of Lau (Plates

23, 27) and islands lying in the neighborhood of the Koro Sea present very steep angles.[1] This angle in places exceeds 30° or even 35°. The slope is generally littered with huge spheroids of andesite. The basalt forms a much more gentle slope, as may be seen by a traverse of Taviuni. Usually the basalt is in very inconsiderable quantity and appears to be of younger date than the andesite.

THE RECENT AGE OF THE VOLCANIC PHENOMENA.

There appear to have been two distinct flows, one of andesite, the other of basalt. Both appear to be very recent, even subsequent to the last upheaval at Lau. Wherever volcanic rock is found in the smaller islands of Fiji, whether that island be wholly volcanic or part volcanic and part limestone, the eruptive rock is disposed of in gradually sloping hills, with heaps of lava blocks scattered indiscriminately, or takes the form of streams of volcanic stones littering the beaches.

At Mango, Thithia (Plates **15**, **16**, **19**), Vanua Mbalavu, and Yathata, cliffs of limestone exist forming inliers in flows of andesite lava. It would seem that a great stream of andesite descended from higher levels, parted near what is the inlier, and then swept over the cliff on either side, and became confluent again at its base, where the lava was by degrees piled so high as to be nearly on a level with the top of the cliff, and so produced a steep embankment sloping in one direction back towards the base of the cliff inlier, and in the other direction towards the general trend of the lava flow. The contour of the lava bank as it lies under the cliff suggests that of a viscous mass flowing round a large obstacle and grown stiff before it had completely enveloped the obstruction.

In Mango huge sections of strata may be seen exposed in gullies that have cut through the lower parts of the hill slopes (Plate **2**, Figs. 2, 3). These strata have a decided dip, and consist of andesite tuffs with large angular blocks of limestone scattered through the rock mass. These blocks are as much as a ton in weight, and consist of coralline rock indistinguishable from the present reef mass. A similar phenomenon occurs in the 9-fathom lagoon to the south of Mango, where the tuff beds are similar to those before described (*vide* map of Mango, Plate **1**). The volcanic agglomerate is therefore clearly newer than the raised reef limestone, and is in turn capped in places by a flow of andesite lava.

The shape of the island of Vanua Mbalavu has been determined by a line of volcanic vents, while its north and south extremities consist of lofty limestone escarpments. Silicified corals lie on the summits of the razorbacks and higher slopes of Vanua Mbalavu, and are evidently examples of silicification by contact metamorphism through percolation into reef coral of superheated water derived from the volcanic rocks.

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[1] See A. Agassiz, *l. c.*, Plates 34, 46, 48, 50, 57, 58.

At Mango and Thithia similar silicification may be noticed.

On Mango, a spring draining the north side of a volcanic mass 600 feet in height suddenly disappears in an enormous mass of limestone. This point of disappearance is at the 50 feet level above high-water mark, but almost immediately above this another andesite mass rises seawards to a height of 150 feet above the sea in such a position that it is interposed between the point of disappearance of the stream and the sea-shore. The distance thence to the coast is 500 yards; the stream, which is of considerable volume, reappears on the beach 600 yards away. It is far more probable that the water worked its way through a limestone substratum than that it percolated through the more or less impervious andesite. If this is so, the volcanic rock must here be above and newer than the limestone.

At the south of Vanua Mbalavu a hot spring bubbles up through the limestone near the tidal zone. The temperature, though below boiling-point, is high enough to scald the skin. At times the water in the adjacent lagoon becomes heated over a small area. About 30 yards distant from the first spring, another hot spring occurs in the midst of a limestone fissure.

Both these springs are in close proximity to the junction line between what, in my opinion, is one of the latest intrusions of andesite and the old reef rock.

At Naitamba, Tuvuthá, and Kambara [1] the old lagoon floors are still intact.[2] Mango and Thithia were doubtless once possessed of similar lagoon hollows prior to the great covering of volcanic alluvium which now hides the old limestone floor. Consequently, if this reasoning is right, these lagoons antedate the chief volcanic outbursts.

Calcareous deposits obscure everything along the coasts of Lau with the exception of the volcanic rock, whether in dome-shape, dyke-form, or as tuffs. The enormous rolling hills of andesitic lava that have spread out from the cliffs have no trace of limestone or calcareous material attached to their sides, except at Kambara, where whitened, burnt blocks of limestone litter its rounded volcanic hill; these, however, represent unmistakably disrupted cliff masses, and are the broken fragments resulting from the volcanic outbursts.

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[1] See A. Agassiz, *l. c.*, p. 74.

[2] At Kambara certainly not. — A. Agassiz.

The Volcanic Rocks.

A good collection of volcanic rocks of the more common types from the Fiji area was secured, and a brief summary of their macroscopic and microscopic characteristics is given below.

As regards the general macroscopic features of the Fiji andesites, they may be described as compact, reddish, or greenish rocks weathering into spheroidal blocks, and showing dark green augite and plagioclase phenocrysts in a fine-grained base. The development of the large augite prisms is very pronounced.

In section, two generations of plagioclase are distinguishable: first, a crop of large idiomorphs with corroded edges, and showing well-developed concentric zoning. These also show albite twinning, and their general outline is tabular, although often they occur in nests or bunches, one crystal being partly or wholly enclosed by others. Next, a crop of small lath-shaped sections. The "felt-like aggregate of feldspar microlites" so characteristic of andesites is also well marked. The augites constitute an important factor in the mass. They are usually represented as monoclinic prisms, yielding octagonal sections, and showing concentric zoning, and twinning parallel to the orthopinacoid in a marked degree. Rhombic pyroxene polarizing in high colors and almost indistinguishable from olivine in thick sections is also common. The augite is often replaced by viridite. The following are some detailed descriptions of some of the thin sections I prepared of the Fiji volcanic rocks: —

No. 1. *Levuka.* Specific gravity, 2.9. A compact augite-andesite. The augites are in the form of phenocrysts and yield fine octagonal sections. Concentric zonal structure and twinning parallel to the orthopinacoid is common. Two generations of plagioclase, the older and larger showing kaolinization and concentric zoning, the newer crop consisting of lath-shaped sections. The augite has been replaced by viridite in places, and much magnetite is scattered throughout a felt-like base. This is a fragment from a lava agglomerate.

2. *Mango.* Specific gravity, 2.57. Taken from a lava flow. An extremely dense andesite with idiomorphs representing the first crop of plagioclase. The "andesite" ground mass is well developed, and large particles of magnetite occur in a great development of magnetite specks.

3. *Munia.* Specific gravity, 2.70. Taken from an andesite agglomerate. Vesicular to cellular lava. Phenocrysts of plagioclase twinned on albite type. Shows the "felt-like base." The felspar is much decomposed and the magnetite is well developed.

4. *Totoya.* Specific gravity, 2.7. Sample from lava flow. This is an andesite, much decomposed. Rock generally green, owing to decomposition of augitic ground-mass into viridite. The felspar of the first generation shows advanced kaolinization, and great abundance of lath-shaped crystals of felspar.

5. *Munia.* Specific gravity, 2.55. Specimen from lava agglomerate. A cellular andesite lava. In section, shows a few pyroxenes polarizing in high colors, also plagioclase idiomorphs in a fine "andesite" base. Zonal structure is found in the felspars and spherulitic structures are common.

6. *Taviuni.* Specific gravity, 2.66. Vesicular lava. Described more fully later. A fine-grained black rock. Yields in section phenocrysts of plagioclase set in a base of closely packed lath-shaped felspars and the "felt-like" material common in andesites. Magnetite is common, and also olivine or pyroxene.

7. *Singatoka River.* Specific gravity, 2.71. Porphyrite in agglomerate form. Large greenish plagioclase crystals in brown base containing second growth of minute felspar crystals.

8. *Levuka.* Specific gravity, 2.8. Reddish andesite with porphyritic development of green augite showing perfect idiomorphic contours. Felspars of first generation much decomposed and corroded in the andesite magma. This felspar occurs in nests. Zonal structure well observed in felspars. Spherulites present as well as much magnetite. Abundance of pyroxene decomposition products.

9. *Totoya.* Specific gravity, 2.7. A greenish augite-andesite. Similar to No. 4, but not so decomposed. Shows well-developed plagioclase crystals in fine base with scattered magnetite as fairly large grains or well-distributed specks. Second crop of lath-shaped felspar crystals. Augites and pyroxene phenocrysts, the former showing zonal structure at times. Fair examples of spherulites.

10. *Mba Vatu.* Specific gravity, 2.85. Selected from tongue of compact reddish andesite lava, with glistening felspar crystals. Shows in section well-defined plagioclase crystals and phenocrysts of augite with the usual accompaniment of lath-shaped felspars. This rock exhibits the "felt-like base structure" with great development of magnetite specks. Twinned augites occur.

11. *Levuka.* Specific gravity, 2.8. Very compact andesite agglomerate, almost identical with (8).

Mr. W. E. Woolnough, B. Sc. of Sydney University, has kindly examined and described No. 12.

No. 12. *Suva.* Specific gravity, 2.84. Olivine dolerite.

Plagioclase by far the most abundant constituent of the rock, making it almost andesitic. They take the form of large tabular crystals with abundant concentric-zoned inclusions, mainly magnetite and a little apatite. The zoning is very perfect. Augite is present in large yellow idiomorphic crystals showing twinning and traces of ophitic structure.

The olivine present is a highly ferriferous variety, some of the crystals being blood-red. Most of the olivine is in the form of large grains, some show distinct outlines. Some of it is almost undecomposed, while some is almost opaque with secondary serpentine and iron-oxides.

The magnetite recurs in scattered grains, and is distributed abundantly throughout the ground mass, which is crypto-crystalline to glassy in texture. In one cavity there is a mass of small spherulites of a zeolite. These give under crossed nicols a dark cross at about 30° with the principal planes of the nicols.

13. *Mango.* Specific gravity, 2.75. Selected from compact andesite flow. Shows the usual structure and appearance of plagioclase. The pyroxenes are altered; some show beautiful 8-sided crystals. Much magnetite present.

14. *Taviuni.* Specific gravity, 2.70. Selected from vesicular andesite. Under microscope shows two crops of felspar in glassy base. Great development of magnetite.

15. *Taviuni.* Specific gravity, 2.72. Vesicular olivine basalt. The olivines are quite fresh. Crop of lath-shaped felspars.

16. *Munia.* Specific gravity, 2.70. Taken from an andesite agglomerate. Dark-colored rock showing usual two crops of plagioclase in fine base. Pyroxenes are altered.

The following three rock slides were described by Mr. W. E. Woolnough, B. Sc., of Sydney University.

17. *Loma Loma.* Specific gravity, 2.92. This appears to be a coarse dolerite with phenocrysts of striated felspar, and apparently greenish pseudomorphs after olivine.

18. *Suva.* Specific gravity, 2.57. A rhyolite.

Groundmass is crypto-crystalline, containing abundant grains of limonite, also containing very abundant small spherulites which are quite free from limonite.

The phenocrysts are quartz orthoclase, plagioclase, and a little decomposed biotite. They are all more or less idiomorphic and are more or less corroded by the magma. They all contain inclusions which are gaseous, glassy, or lithoid. Apparently there are no liquid inclusions. The felspars are all clear and glassy and are distinguished from the quartz and from each other by the nature of the twinning. The inclusions are more or less symmetrically arranged.

There are three or four decomposed basal sections of biotite. These contain grains of magnetite.

19. *Mango.* Specific gravity, 2.75. Olivine anamesite.

The plagioclase is of two generations, — the older in tabular, cleaved, and corroded crystals, showing zoning in places, and the newer crop is in the form of acicular microlites felted together. The olivine is very abundant and in places shows large idiomorphic grains. Only slightly serpentized. The augite is scattered through the rock in almost colorless granular aggregates. Magnetite occurs as irregular grains in great abundance. Apatite is also present in small stumpy prisms, especially as inclusions in the older felspars. The groundmass of the rock is crypto-crystalline and colorless.

Professor David of Sydney University also describes a section from Mango.

20. *Mango.* Olivine basalt.

This olivine basalt taken from the beach at Mango has in thin section a very fresh appearance. It is formed of irregular granules of olivine fairly free from decomposition, though slightly serpentinized at the edges; clear phenocrysts of plagioclase and smaller felted crystals with small augites and numerous magnetites in a crypto-crystalline base.

The magnetites are all bounded by sharp edges, and are remarkably free from traces of decomposition.

The whole rock has a decidedly fresh appearance.

The Limestones of Fiji.

Viti Levu.

The Older Limestones of the Main Island. — This is a compact limestone of bluish-yellow color, and possessing a dip of 50°. It appears to be connected with the dolomites of the upper river. It will be remembered that this rock underlies the shelly limestone of the Thuvu-Singatoka area.

The Dolomites. — A rock of an extremely compact nature and homogeneous in texture. Generally it is white or yellowish brown in color. It is apparently non-fossiliferous. It weathers to that bluish color on the escarpment faces so admirably seen in many Silurian limestones. The lilliputian mountain-range structure is well exemplified on weathered surfaces. — Specific gravity, 2.71.

The Shelly Limestone of the Main Island. — In patches it is white in color, but generally preserves a tint varying from light yellow to rich brown or red. In the softer sandy beds there is no fracture, as the rock crumbles beneath the finger, but in the sparely fossiliferous beds the fracture is flat. This freestone exhibits a wonderful evenness of texture, consisting of small calcareous sand particles compacted into solid rock. In other beds, again, although area for area there is a general uniformity of appearance, still in any small individual block there are vast deviations from any common standard of homogeneity that may be set up. Concretions occur which, when struck with the hammer, emit sparks, and are exceedingly difficult to break, while round them may be clustered roulettes of foramens lying in loosely cemented sand. These petrifactions have conchoidal fractures, and are exceedingly compact and minute in structure. A cliff face may present the curious effect of a soft exposure, dotted over with hard sub-cylindrical protuberances standing out five or six inches from the vertical face. All the beds are extremely porous. A small patch of coral reef has been sandwiched in between a bed of greasy clay and a fine-grained limestone. From a short distance the cliffs with their uniform and persistent lines of stratification, their warm brown and yellow tints, and their "rock-shelter" development, have striking similarity to some of the Triassic arenaceous sandstones of the Sydney district, but the age of the Fiji rocks is of course very different, being probably Tertiary.

What has just been said concerning the Thuvu-Singatoka area is true also for the calcareous beds near Suva. Here also the rock, considered in belts, is fairly homogeneous.

Calcareous Rock and Coral Rock passing into Soapstone. — On the west side of Suva harbor beds occur that pass gradually from soapstone to a sandy limestone rock. There is no sharp line of demarcation. The one shades insensibly into the other. Exteriorly it often presents a rough and hard appearance, but breaks down under the hammer into a sandy clay rock. At various times large serrated *Carcharadon* teeth, carapaces and plastra of turtles have been unearthed from the Suva stone. The rock is rarely cavernous and contains few fossils.

THE LAU LIMESTONES.

(*a*) A soft, porous stone, full of corals *in situ*, shells, and a little calcareous cement. The corals are no more compacted than one would expect to find in the reef area. The stone is usually white or yellow in color. A thin crust of hard material has gathered over the soft interior. This crust, as well as the reef or coral talus itself, is extremely cavernous. This represents the raised coral material of the last upheaval.

(*b*) A dense white rock, ringing under the hammer, generally exhibiting little or no trace of well-defined fossils. This is the raised limestone found near sea-level; it is contemporaneous with (*a*), and represents the part of the "raised reef" platforms that is composed of the firmly cemented reef débris.

(*c*) A compact stone ringing under the hammer containing corals. The color is white or yellow. It is pitted and cavernous, and weathers into long needles. This forms the roughest and most broken country in Fiji. It is the older coral mass of the high levels.

(*d*) A rock similar in hardness, but presenting a marked difference in weathering, due to the difference of erosive influences on a homogeneous rock and one varying considerably in minute structure. The coral reef is honeycombed, while the rock under consideration shows perfect examples of the minute-ridge structures. It is, as a rule, nonfossiliferous and homogeneous in structure. Such rock is found at the higher levels and represents the compact débris of pre-existing reefs. This is well seen at Ngillangillah.

Of other formations we may note a stratified limestone, white, yellow, and brown in color, exceedingly compact and free from honeycombing or cavernous weathering. Very fine-grained rock, and apparently barren of fossils. This is the basal limestone underlying the reefs to the north of Vanua Mbalavu.

A brown to red ferruginous mass, found encrusting the coastal cliffs at sea-levels. In the huge gaps cut out by the sea in the limestone cliffs these ferruginous masses simulate stalactitic and stalagmitic growths. Redeposition of calcareous matter charged with higher oxide of iron than was present in the rock prior to solution, or from the magnetite mentioned before, explains this stalagmitic growth. In some places this redeposition has advanced so far that the former sea-ledges are partly or wholly obscured.

Manganese at Mango and Thithia.

At Mango a great deposit of manganese occurs at a low level (about 100 feet above high-water mark). The earth is decidedly black for a great distance from the surface, being as much as 30 feet thick in places. Large pieces of manganese lie about the ground as scattered blocks.

At Thithia smaller pieces occur. One I picked up was a sphere 1 inch in diameter.

At Naitamba the blocks are of irregular shape, as at Mango.

EXPLANATION OF THE PLATES.

PLATE 1.

Geological map of the island of Mango.

PLATE 2.

Sections across Mango:

1. From Mt. George to Prince Edward's Island.
2. From Mt. Fairhall to Mt. Rupert.
3. Southeast from Mt. Rupert to limestone cliffs.
4. Section across Mango from northeast to southeast.

PLATE 3.

Sections across Singatoka, Tuvuthá, and Mba Vatu:

1. Section across Singatoka River limestones.
2. Section across Singatoka River and sand dunes.
3. Outline of Tuvuthá as seen from Mango.
4. Section of Tuvuthá at right angles to Figure 3.
5. Section through Mba Vatu and Koro Mbasenga.

The position of the older volcanic rocks in Figs. 3, 4, of the sections of Tuvuthá has of course not been observed, and is merely diagrammatic.

PLATE 3a.

Singatoka River, 5 miles from mouth.

PLATE 4.

Horizontal soapstone strata, Thuvu.

PLATE 5.

Raised reef at Thuvu, 11 to 16 feet above high-water mark.

PLATE 6.

Stratified andesite agglomerate near Levuka, Ovalau.

PLATE 7.

Exposure of bedded limestone nearly a mile long, Singatoka Cliff.

PLATE 8.

Volcanic rocks, "The Naivaka," Taviuni.

PLATE 9.

Cliff of nearly 300 feet vertical exposure, northern part of Mango.

PLATE 10.

Slope of later andesite, limestone cliffs in the rear, Mango.

PLATE 11.

Old gap through which interior basin of Mango was once connected with the sea 25 feet above high-water mark, shows also dense vegetation growing on the bare limestones.

PLATE 12.

Miniature lagoon on Mango, eroded probably during a period of rest at the 200-foot level; the old gap (Plate 11) is visible above the pier.

PLATE 13.

Undercut and weathered limestone blocks, Mango. Island of Yathata in the distance.

PLATE 14.

Weathered block of limestone, Mango.

PLATE 15.

Central part of Mango from Mt. Rupert, shows the old gap leading from the interior basin to the sea and the recent andesite outbursts nearly overwhelming the limestone ring.

PLATE 16.

Southwest part of the interior basin of Mango; view taken from Mt. Ryder.

Lettering on diagram facing Plate 16:

a. Mt. Rupert, a recent andesite dome.
b. Block of limestone pushed up by andesite *c*.
c. Andesite that has carried up *b*.
l. Patches of limestone left or not quite covered by lava or alluvium.
m. Limestone agglomerate in volcanic tuff.

PLATE 17.

Central basin of Mango, taken from Mt. Ryder. This view is the continuation of Plate 16. Joins the right of the plate.

Lettering on diagram facing Plate 17:

a. Andesite hills 600 feet high, beyond this the limestone ring, almost buried in its inland development.
b. Block of limestone partly buried by the flow from Mt. Ryder.
c. Limestone mass capped by coral reef 240–300 feet above high-water mark.
d. Volcanic slopes and alluvium downs; the right-hand member of *d* shows fan-shaped spread of lava as it welled round the cliff *c*.

PLATE 18.

Limestone cliffs at Thithia. On the left is shown the typical limestone cliff slope; in the central part is shown a stage in vertical cliff formation.

PLATE 19.

General andesite outburst on Thithia. The little tufts of vegetation on the left mark the site of limestone.

PLATE 20.

Old lagoon outlet on Thithia.

PLATE 21.

Gap in raised limestone, Thithia.

PLATE 22.

Part of Vanua Mbalavu Lagoon, seen from the 600-foot level behind Loma Loma. Yama Yama is the andesite cone in the middle distance with Munia over it and Susui to the right.

PLATE 23.

Andesite slope, Naitamba.

PLATE 24.

Naitamba, looking over the central hollow towards the old lagoon outlet and the broken cliff of the old limestone ring.

PLATE 25.

Vatu Vara (1100 feet high) from the beach.

PLATE 26.

Vatu Vara. Two lines of marine erosion 15 and 30 feet above high-water mark.

PLATE 27.

Sub-horizontal summit of Yathata, showing the sharp line of demarcation between the volcanic and limestone formation indicated by the marked difference in the vegetation. The foreground is a steep andesite slope which has poured over into the limestone in the middle ground. The lava flow is covered with grass, the limestone with a thick forest.

PLATE 28.

Cliff on the western coast of Vatu Leile, showing the vertical cliff, from 100 to 110 feet in height, the long lines of former sea erosion, the "Great Walk," six feet above high-water mark, and the present shelving beach.

PLATE 29.

Flat coast of east side of Vatu Leile.

PLATE 30.

Cliff on west side of Vatu Leile, showing five lines of marine erosion.

PLATE 31.

Vatu Leile cliff of west coast, showing the breaking away of the modern line of marine erosion and that called the "Great Walk," six feet above high-water mark.

PLATE 32.

Junction of raised reef and stratified limestones, Thuvu-Singatoka beach.

PLATE 33.

Stratified limestones, Thuvu-Singatoka beach.

PLATE 34.

Andesite butts, Lakemba.

PLATE 35.

Ngillangillah (520 feet) and the Bay of Islands.

PLATE 36.

Liku, or sea-coast of Vavau (Tonga Islands), showing on the left the disintegration of a soft white cliff and on the right the original slope (? A. AG.) of the cliff.

PLATE 37.

Portion of cliff, 60 feet above high-water mark, showing near the bottom of photograph a large Astræan, partly removed by solution, and near the top of the picture, cavities left after the removal by solution of coral heads, Mango.

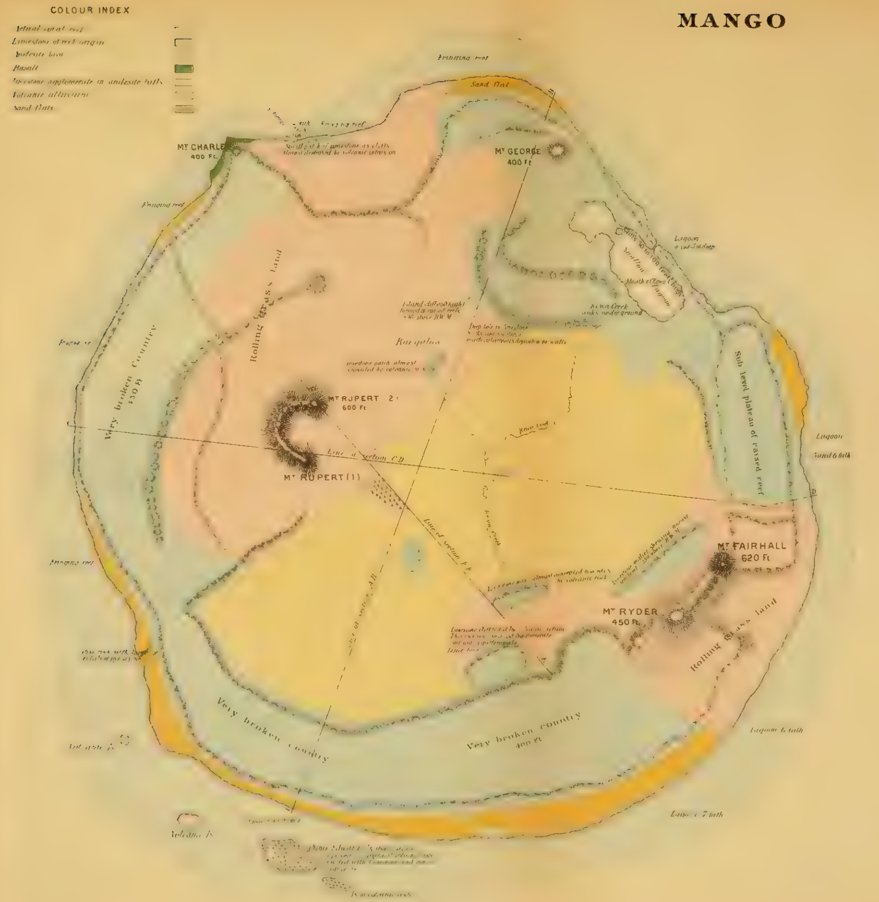
PLATE 38.

Soft cliff face, with hard protuberance, Singatoka River.

PLATE 39.

Upper part of Walu Bay quarry, Suva, showing indistinct lines of stratification.

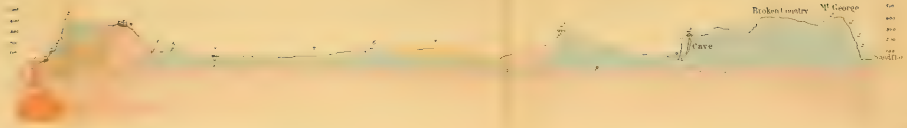
MANGO


COLOUR INDEX
Actual coral reef
Limestone of reef origin
Andesite lava
Basalt
Limestone agglomerate in andesite tuffs
Volcanic alluvium
Sand flats
Mt CHARLES
400 Ft.
Mt GEORGE
400 Ft
Mt RUPERT (2)
600 Ft
Mt RUPERT (1)
Mt FAIRHALL
620 Ft
Mt RYDER
450 Ft
Fringing reef
Sand flat
Very broken country
450 Ft
Rolling grass land
Line of section CD
Line of section EF
Line of section AB
Sub level plateau of raised reef
Lagoon
Lagoon 6 fath
Lagoon 7 fath
Very broken country
Very broken country
400 Ft
Rolling grass land
Mouth of Lagoon
Shallow Lagoon
Volcanic rk
Volcanic rk

Sections across MANGO.

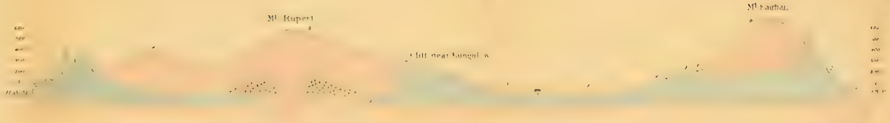
SCALE 4 INCHES TO THE MILE

1



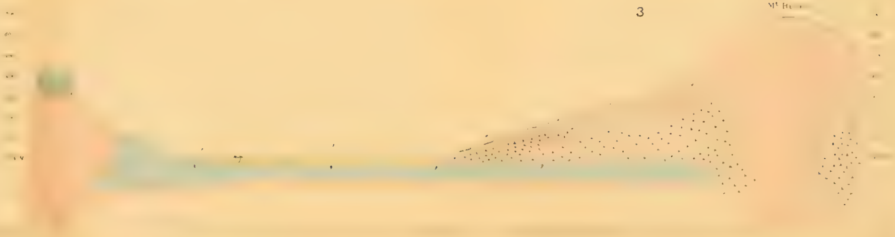
Broken Country
Mt George
Cave
Sandflat

2



Mt Rupert
Mt Fairhau
Cliff near Bungalow

3

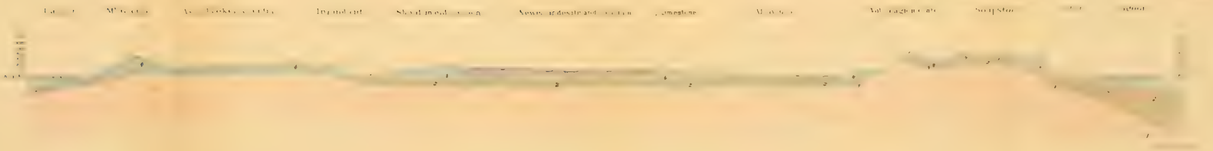


4

Section across MANGO from N E to S

HORIZONTAL SCALE 4 INCHES TO MILE VERTICAL SCALE [illegible] 100 FEET

COLOUR INDEX



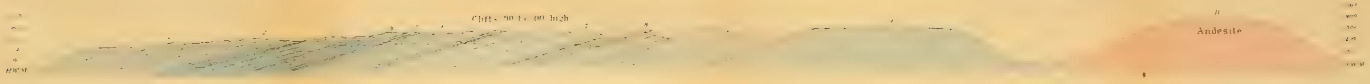
Mt
Limestone
Soapstone

1

Section across SINGATOKE RIVER LIMESTONES

SCALE [illegible] INCHES TO THE MILE

1 Strata cemented beneath subsoil
2 Soft crumbling strata
3 Beds of hard fine grained brown rock
4 Cavern 20 yds long
5 Bed of small [illegible] corals
6 Soft yellow layer containing shells and foraminifera
7
8 Soft crumbling strata
9 Older limestone dipping steeply
10 Flat belonging to Singatoka River
11 Volcanic mass

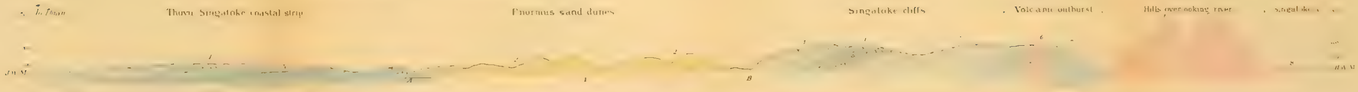

Clifts 90 to 100 high
Andesite
11
H.W.M.

2

Section across SINGATOKE RIVER LIMESTONES AND SAND DUNES Section bent at A and B Distance 7 miles

HORIZONTAL SCALE 3 INCHES TO 1 MILE VERTICAL SCALE [illegible] 100 FEET

1 Limestones dipping similarly to 3 and 5 (Note)
2 Sand dunes 200 high (See note)
3 Soft friable strata
4 Cave and old bed of coral reef
5 Soft yellow fine brown strata
6 Andesite outburst
7 Older limestone
8 Singatoka River


To Thuvu
Thuvu Singatoke coastal strip
Enormous sand dunes
Singatoke cliffs
Volcanic outburst
Hills overlooking river
Singatoka
A
B
1
2
6
8
H.W.M.

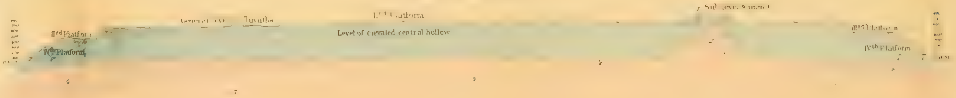
Notes. 1 Dip apparently altered owing to the bending of the sed[illegible]
2 [illegible] sand. These dunes are [illegible] up on the [illegible] Singatoka R. Flat [illegible]

Soft yielded limestone [illegible] Hard compact limestone also older blue limestone [illegible] Andesite [illegible] Sand dunes

3

Outline of TUVUTHA as seen from MANGO

SCALE 3 INCHES TO THE MILE

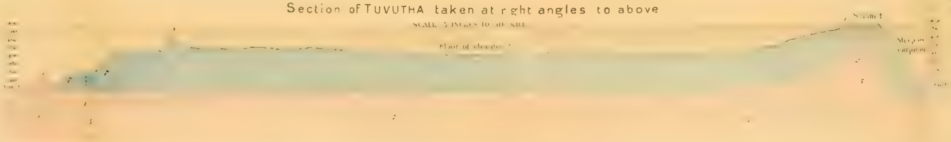

General [illegible] Tuvutha
Ist Platform
Level of elevated central hollow
IIIrd Platform
IVth Platform
IInd Platform
IVth Platform

[illegible] rising of [illegible] rock
[illegible] the base of [illegible] limestone may be substituted
[illegible] to 3 [illegible]
[illegible] the terrace [illegible] by the reef [illegible]
[illegible] These [illegible]

4

Section of TUVUTHA taken at right angles to above

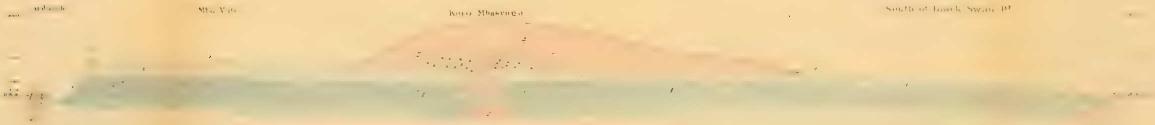
SCALE 3 INCHES TO THE MILE

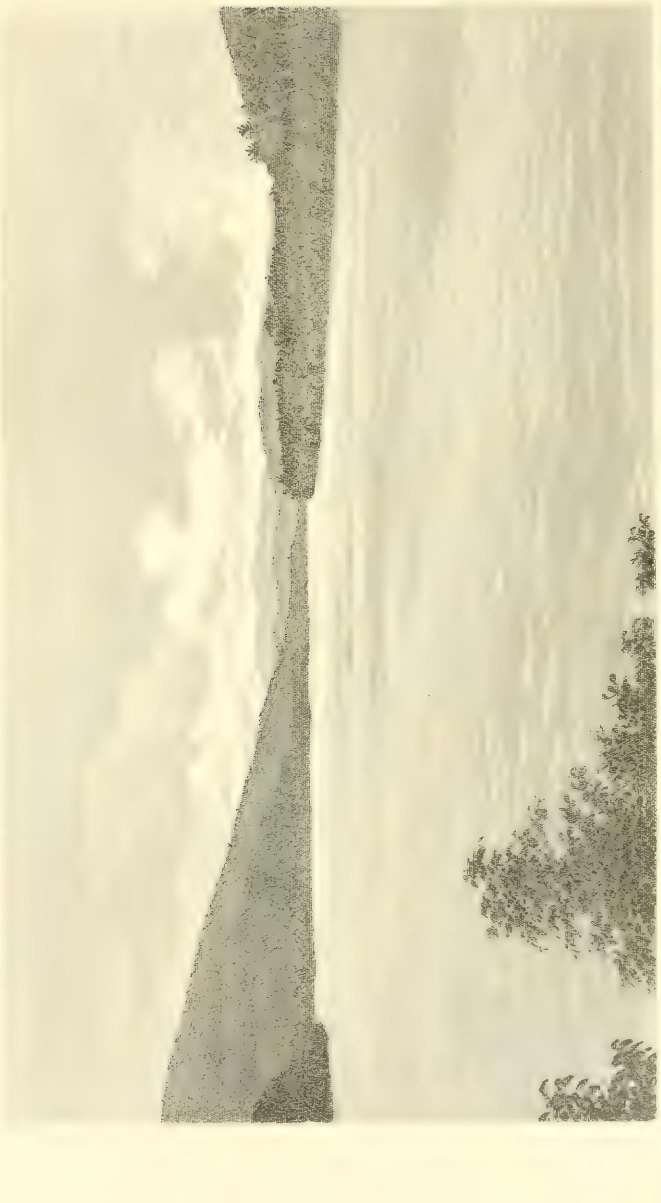

Floor of elevated [illegible]
Summit
Steep [illegible]

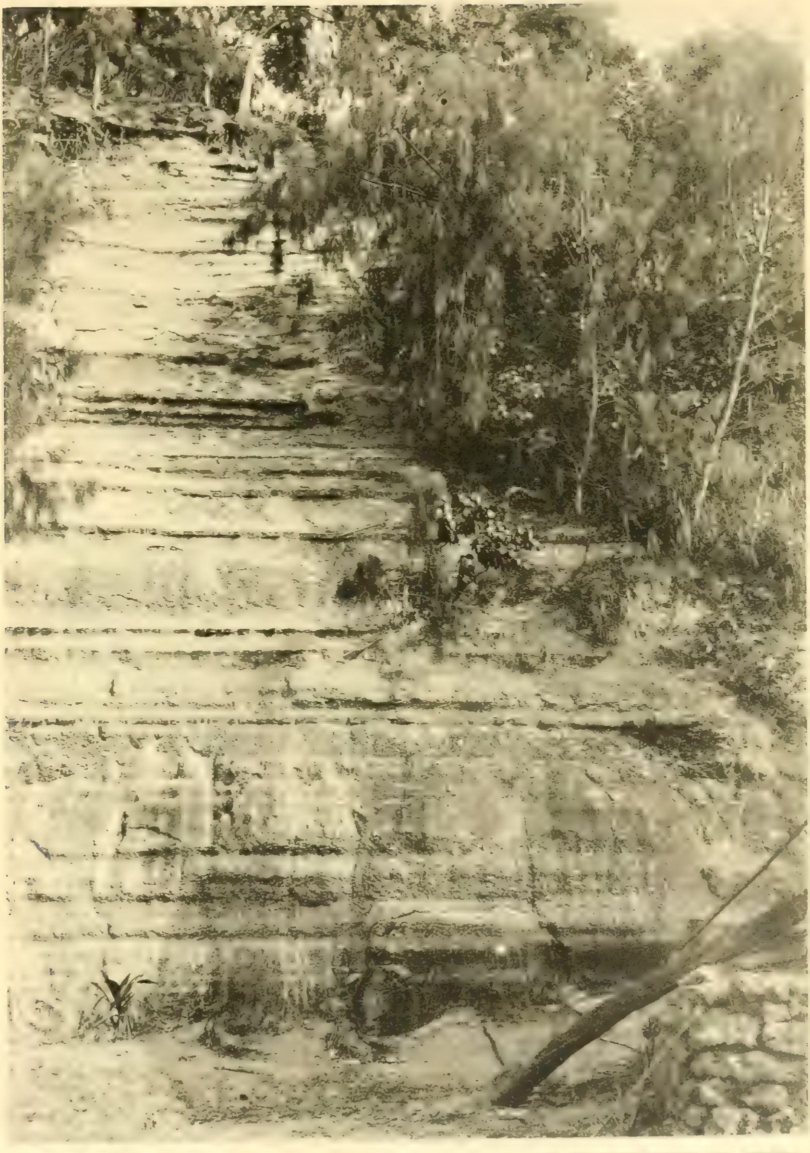
5

Section through MBA VATU and KORO MBASENGA

SCALE [illegible] INCHES TO THE MILE


Mba Vatu
Koro Mbasenga
South of Black Swan Pt
1
2

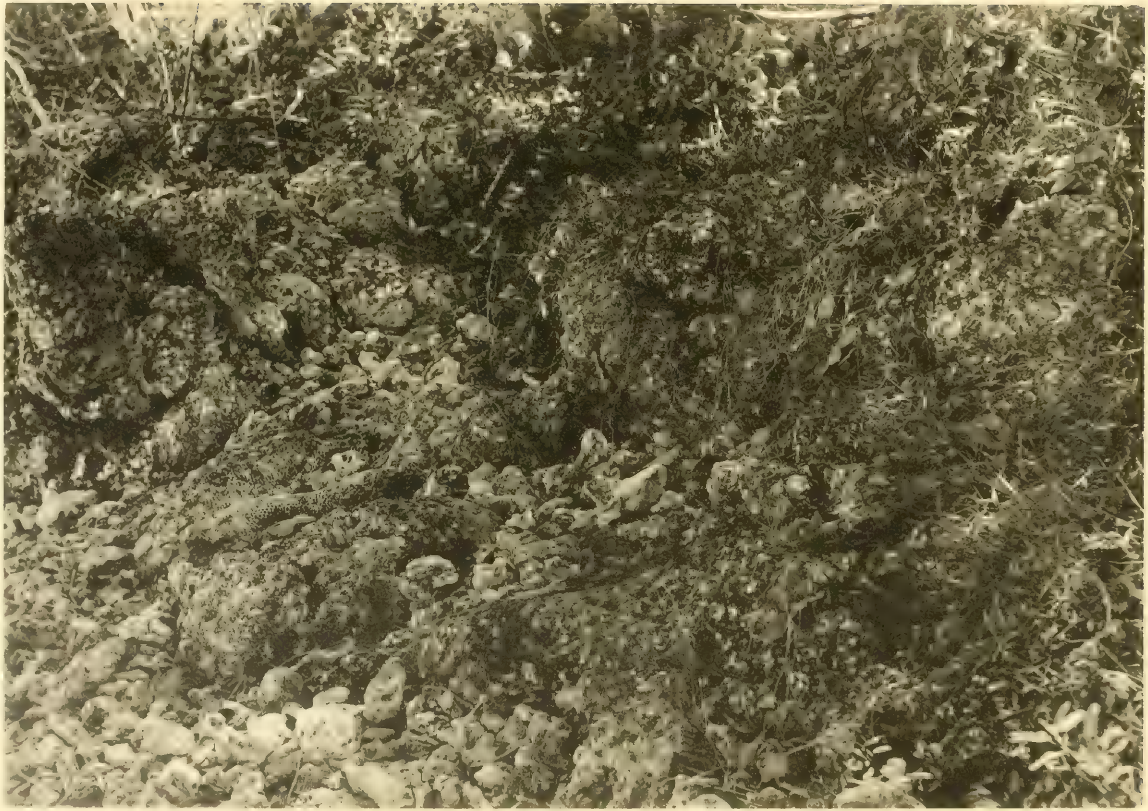




ANDREWS PHOTO.

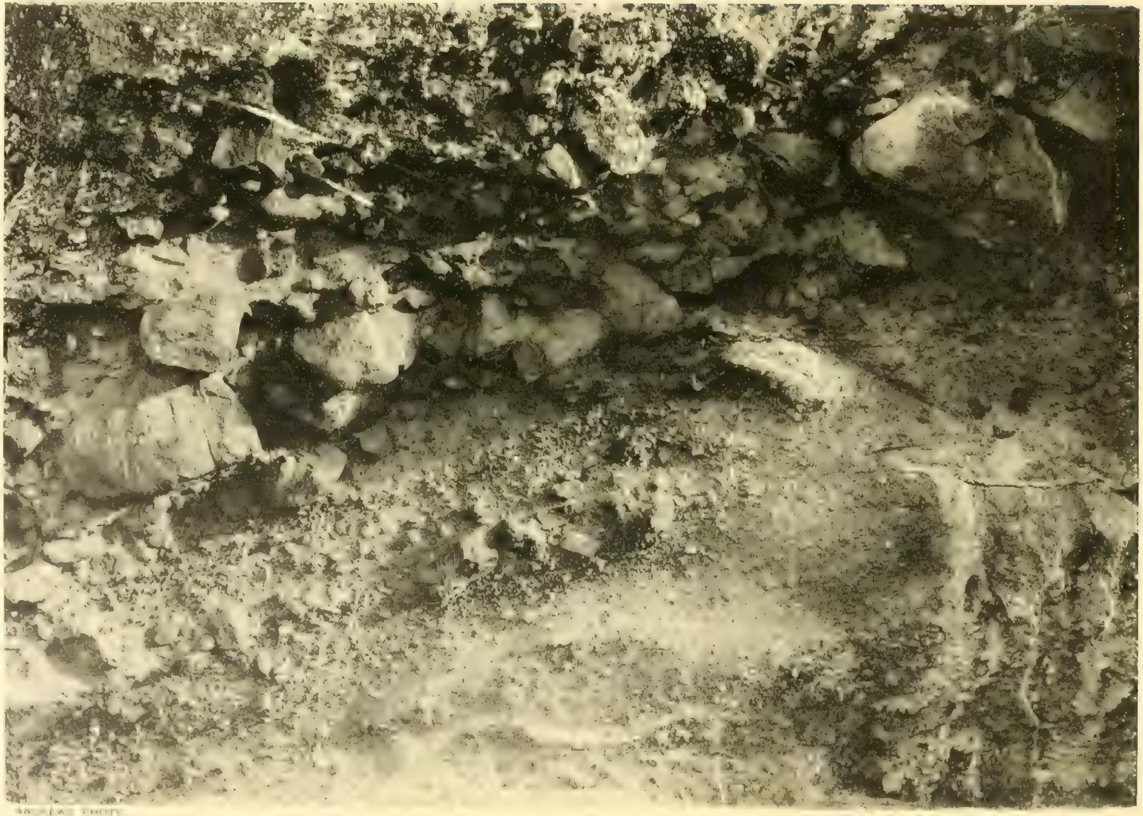
THE HELIOTYPE PRINTING CO. BOSTON.

HORIZONTAL SOAPSTONE STRATA, THUVU



THE HELIOTYPE PRINTING CO. BOSTON

RAISED REEF, THUVU



ANDREWS PHOT.

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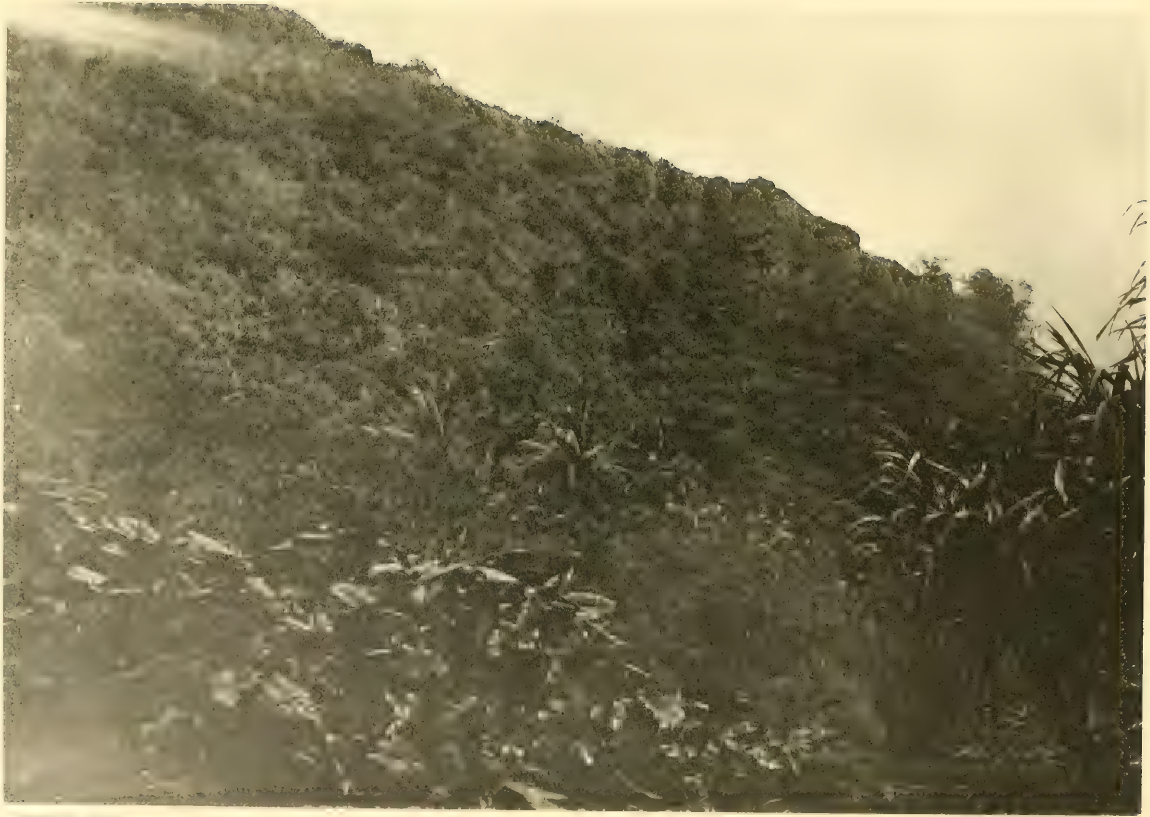
ANDESITE AGGLOMERATE OVALAU



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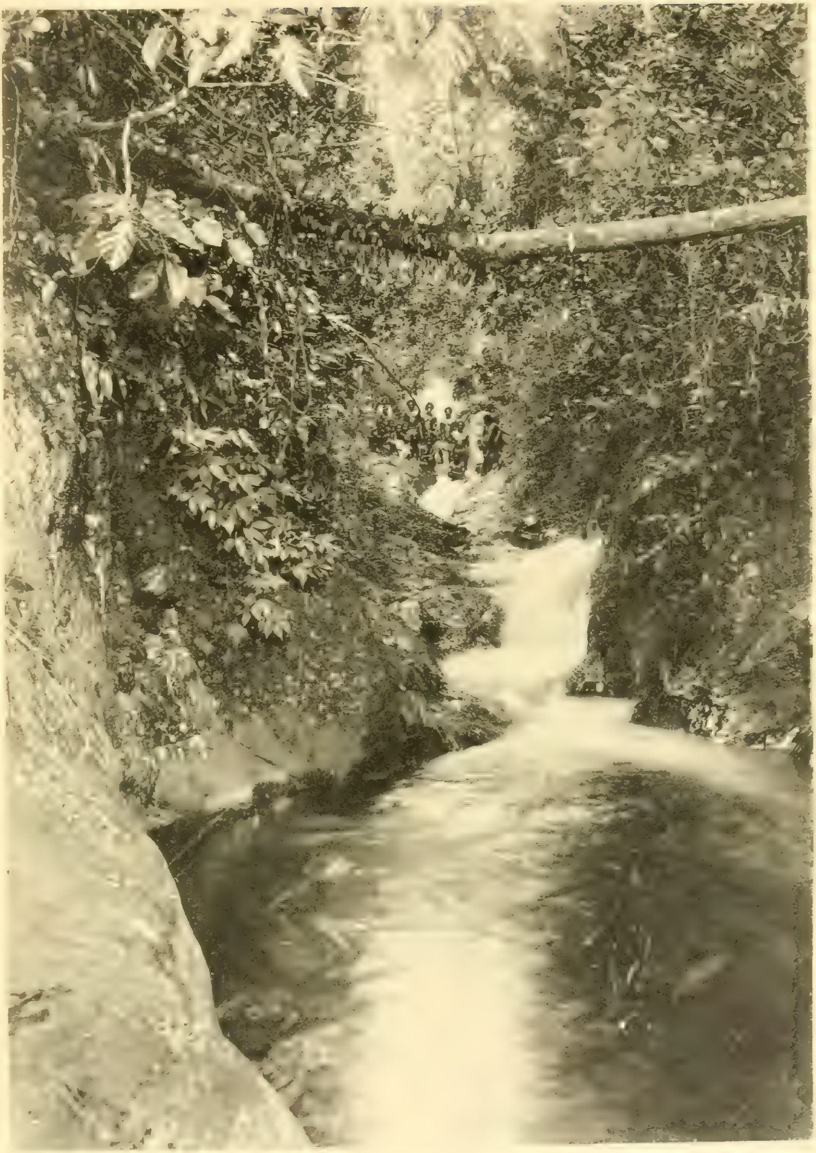
BEDDED LIMESTONE CLIFFS SINGATOKA



ANDREWS PHOTO

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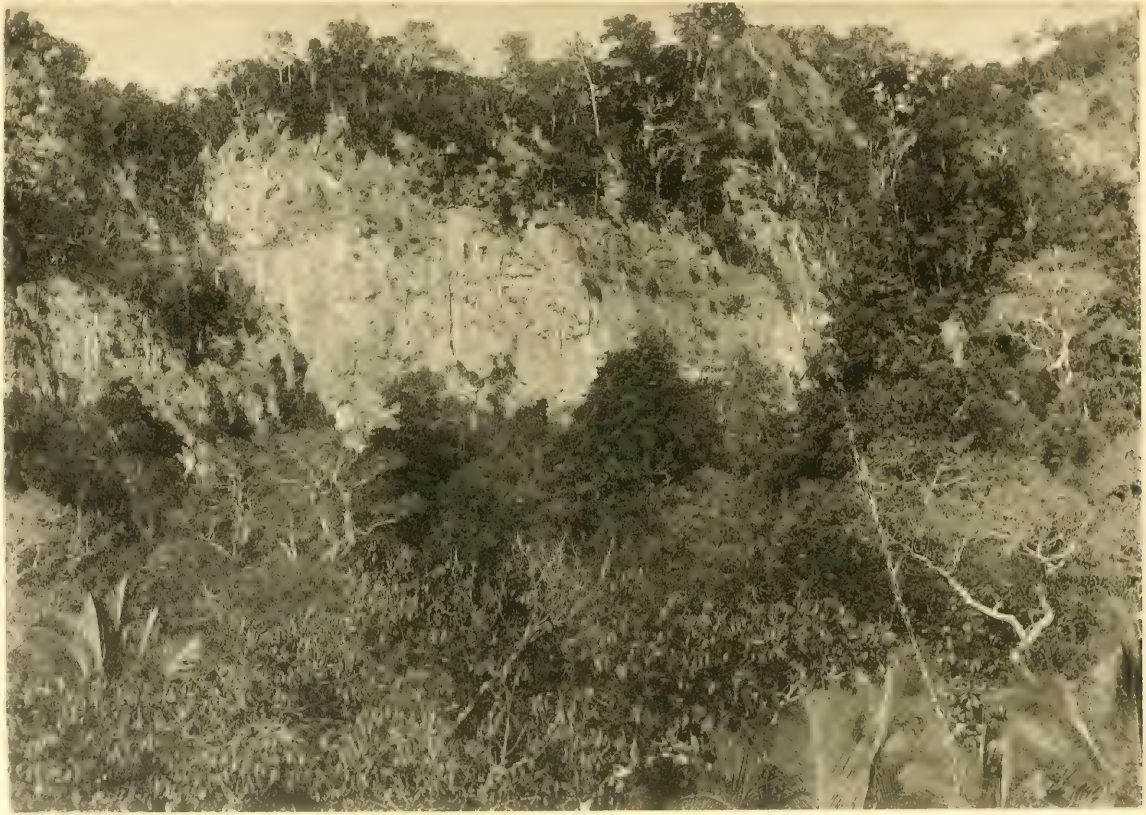
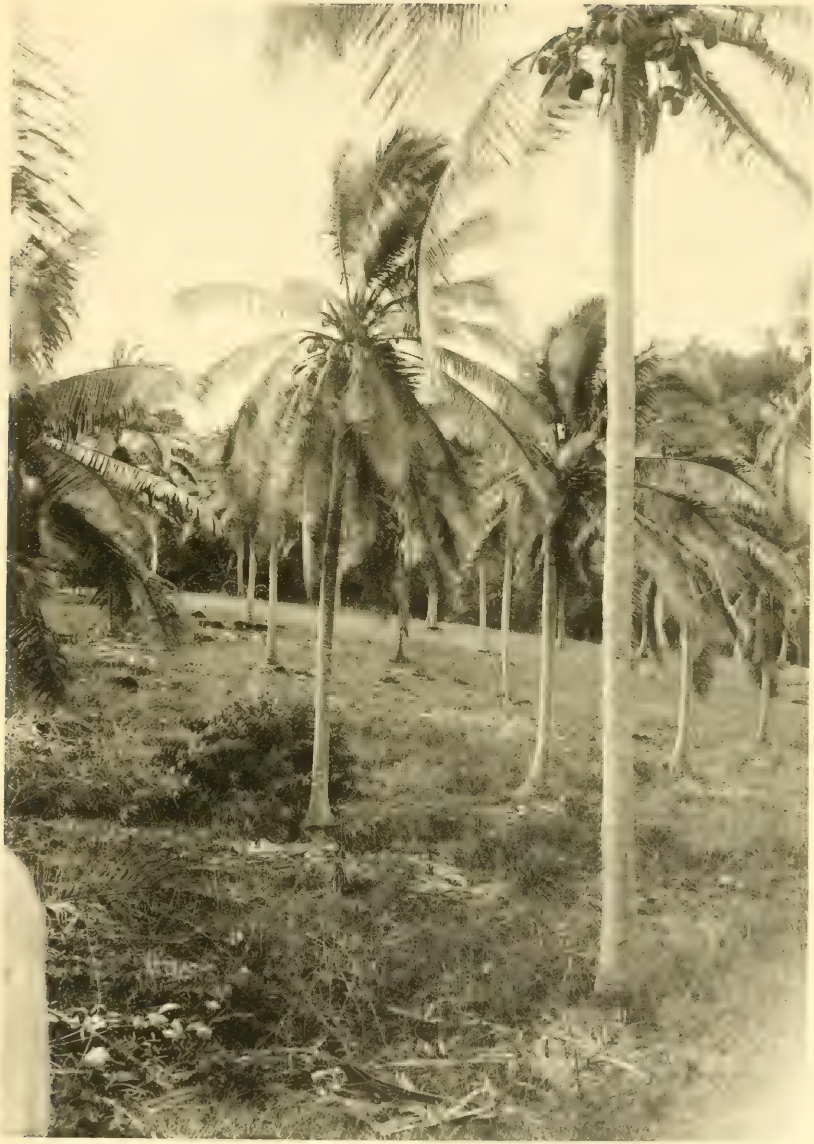
VOLCANIC ROCKS, TAVIUNI.



[illegible] PHOTO

THE HELIOTYPE PRINTING CO. BOSTON

LIMESTONE CLIFF, MANGO.



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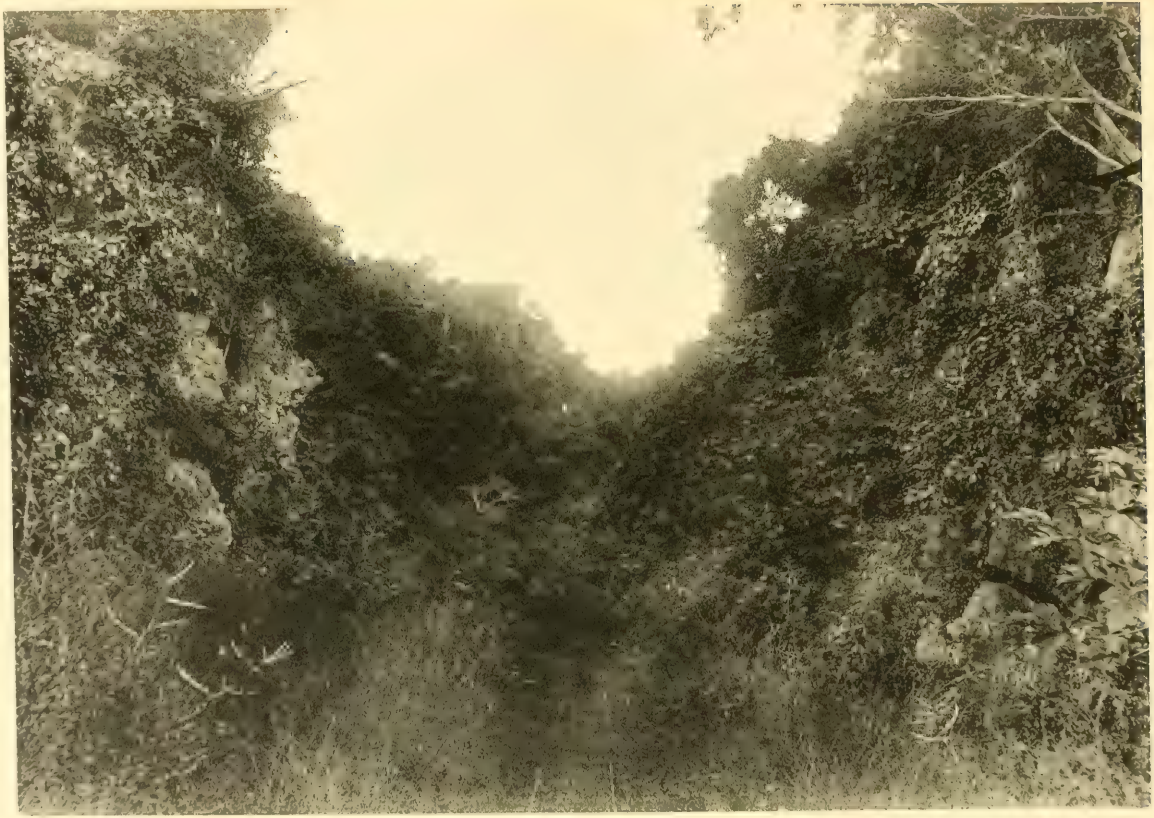
ANDESITE SLOPE, MANGO



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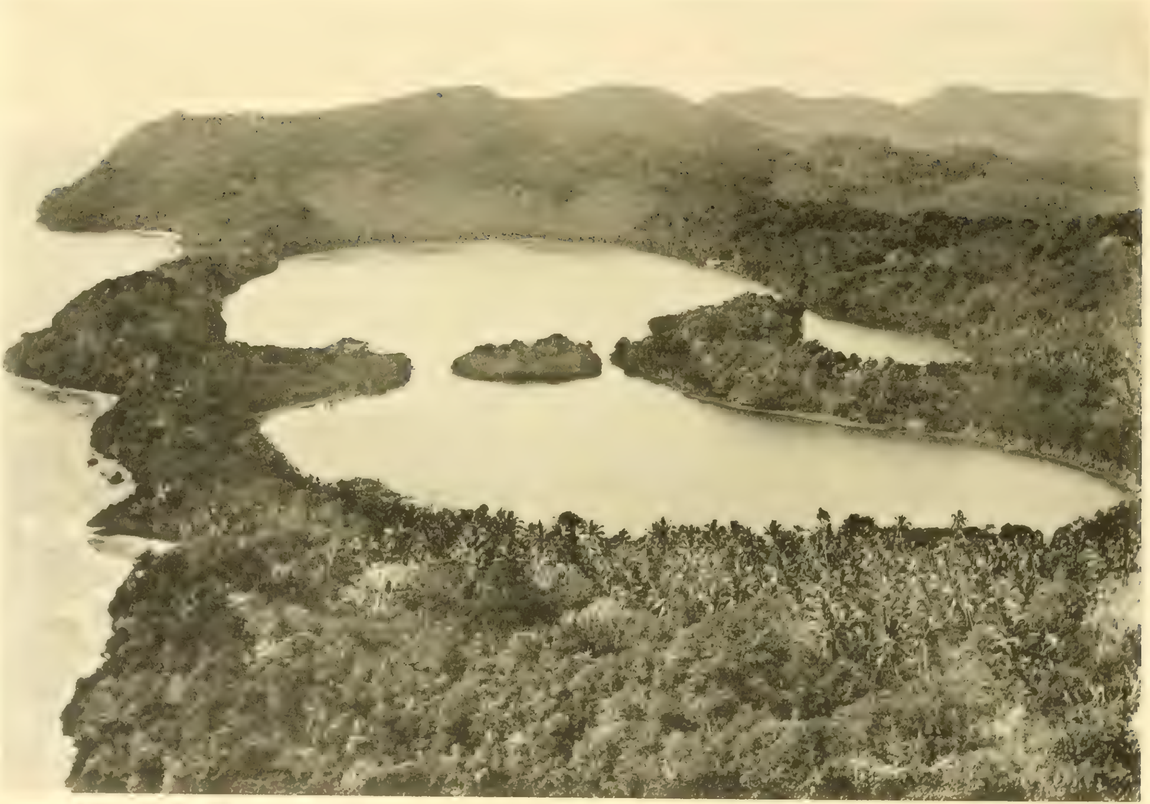
OLD GAP, MANGO



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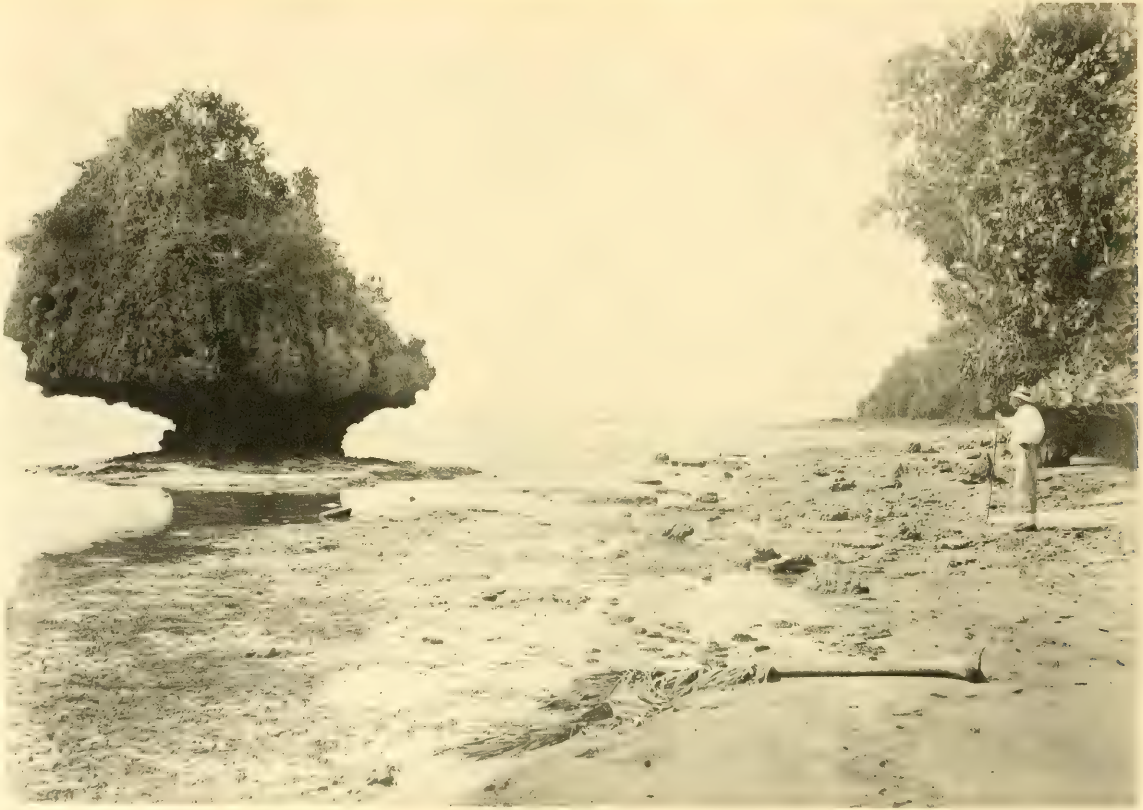
MINIATURE LAGOON, MANGO

PLATE 13.



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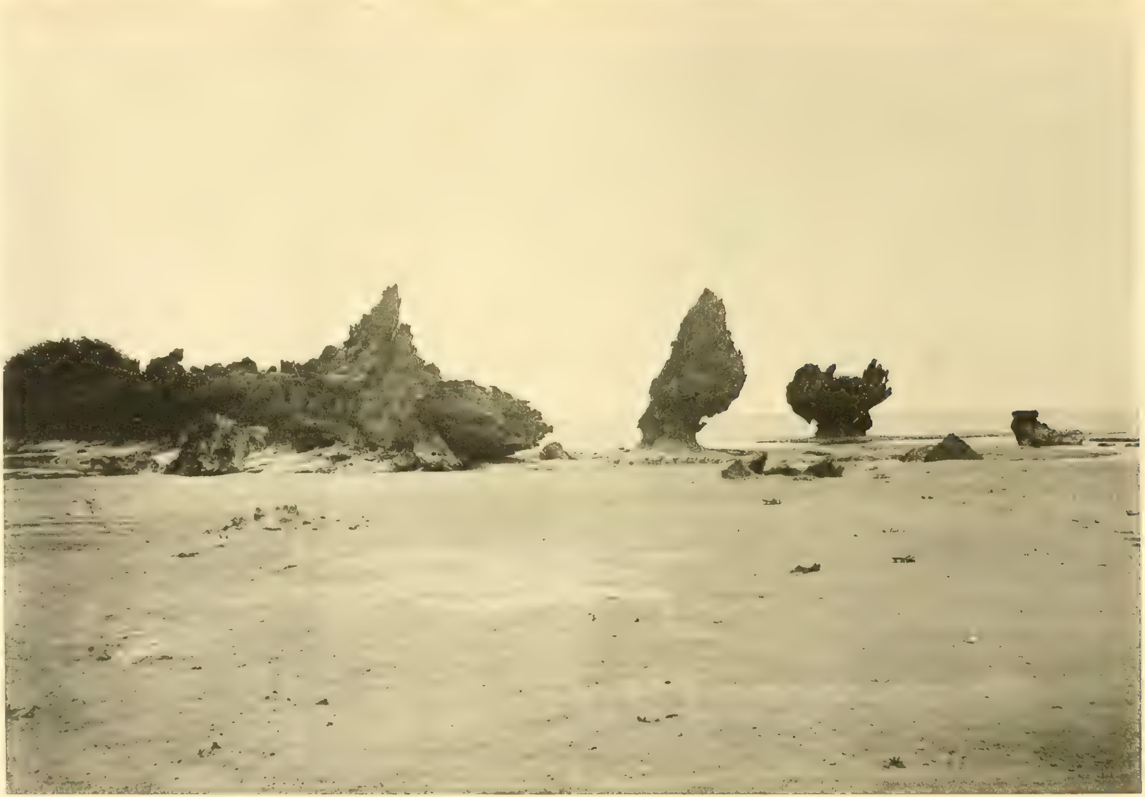
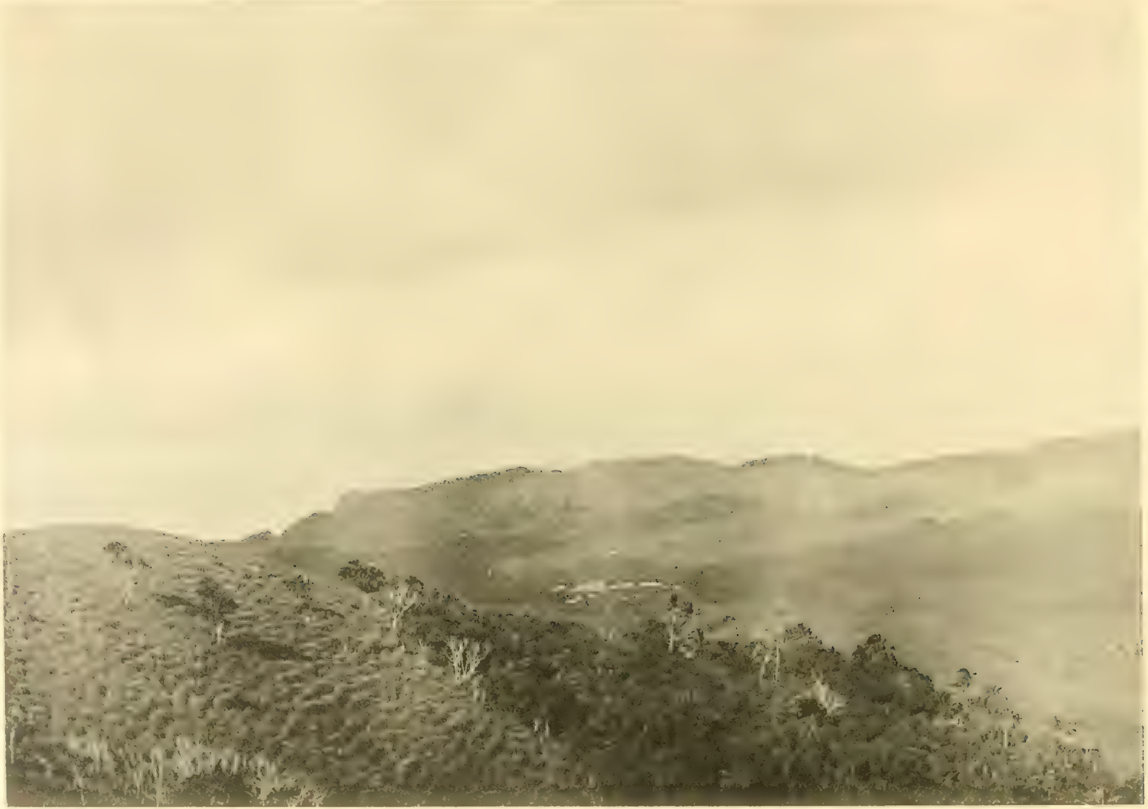
WEATHERED LIMESTONE BLOCKS, MANGO



ANDREWS PHOTO. THE HELIOTYPE PRINTING CO., BOSTON.

WEATHERED LIMESTONE BLOCK, MANGO



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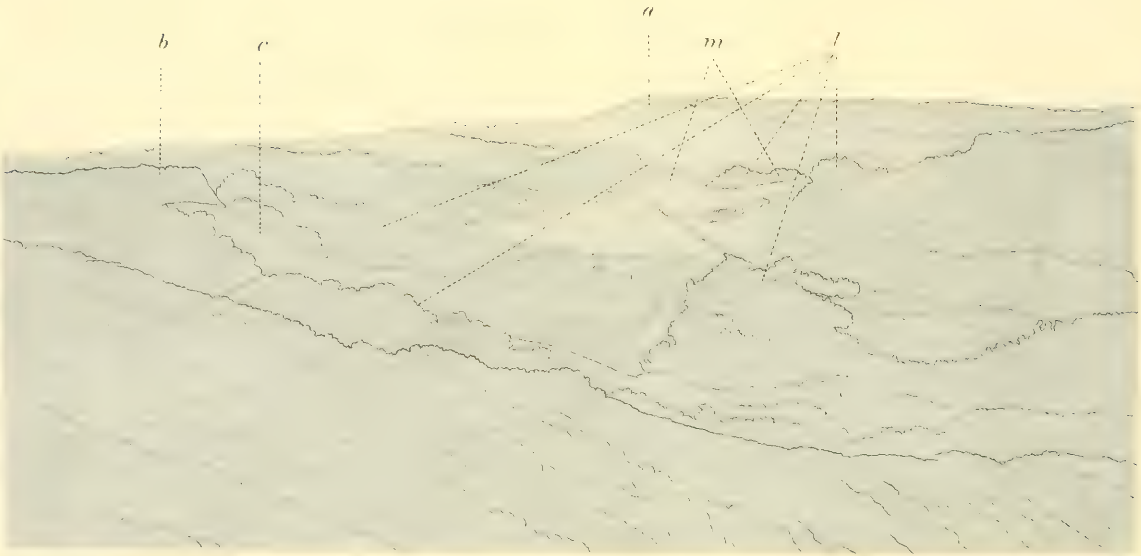
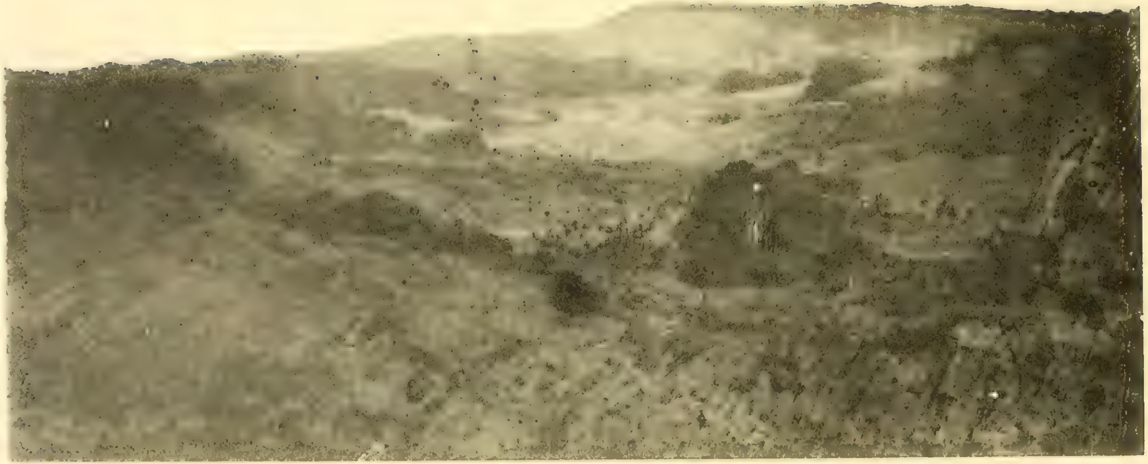
CENTRAL PART OF MANGO.

AUVERGNE—FIG. 1

FACE PLATE 16





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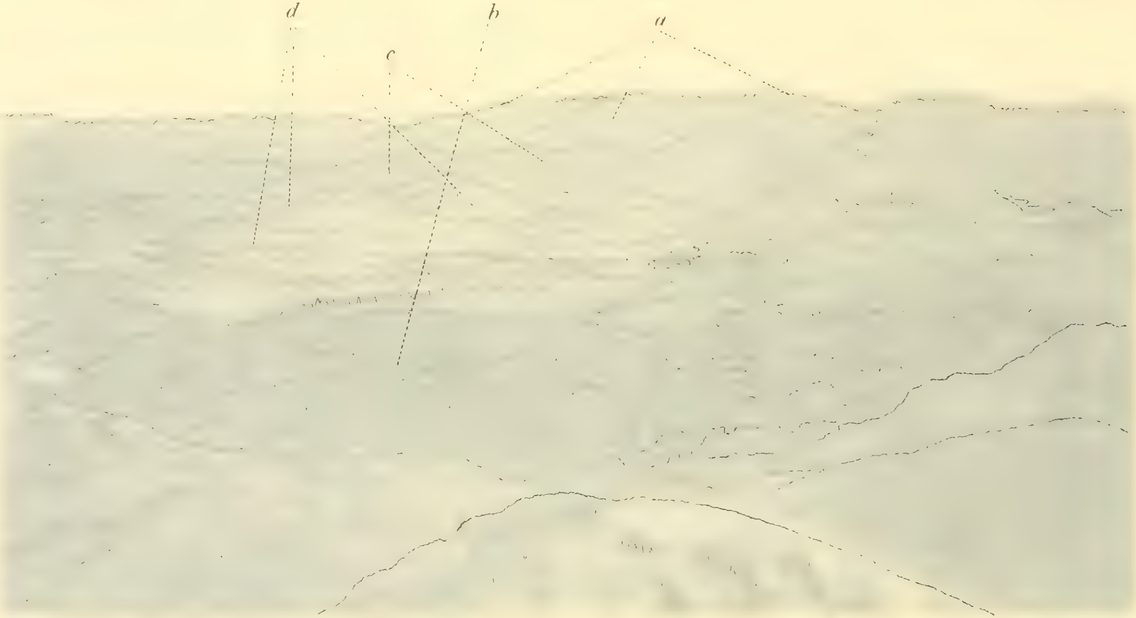
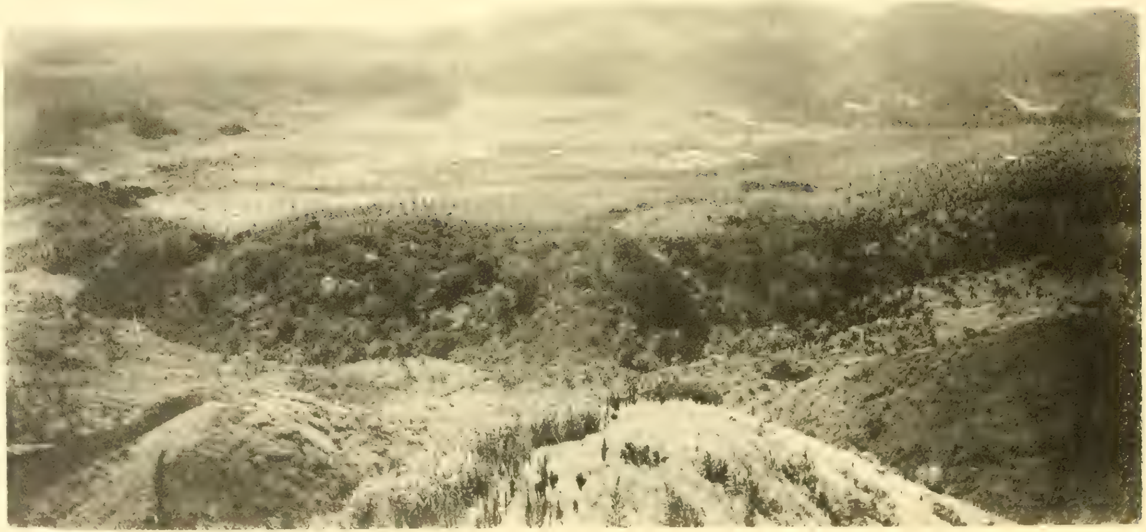
THE HELIOTYPE PRINTING CO., BOSTON.

INTERIOR BASIN. S. W. PART OF MANGO.

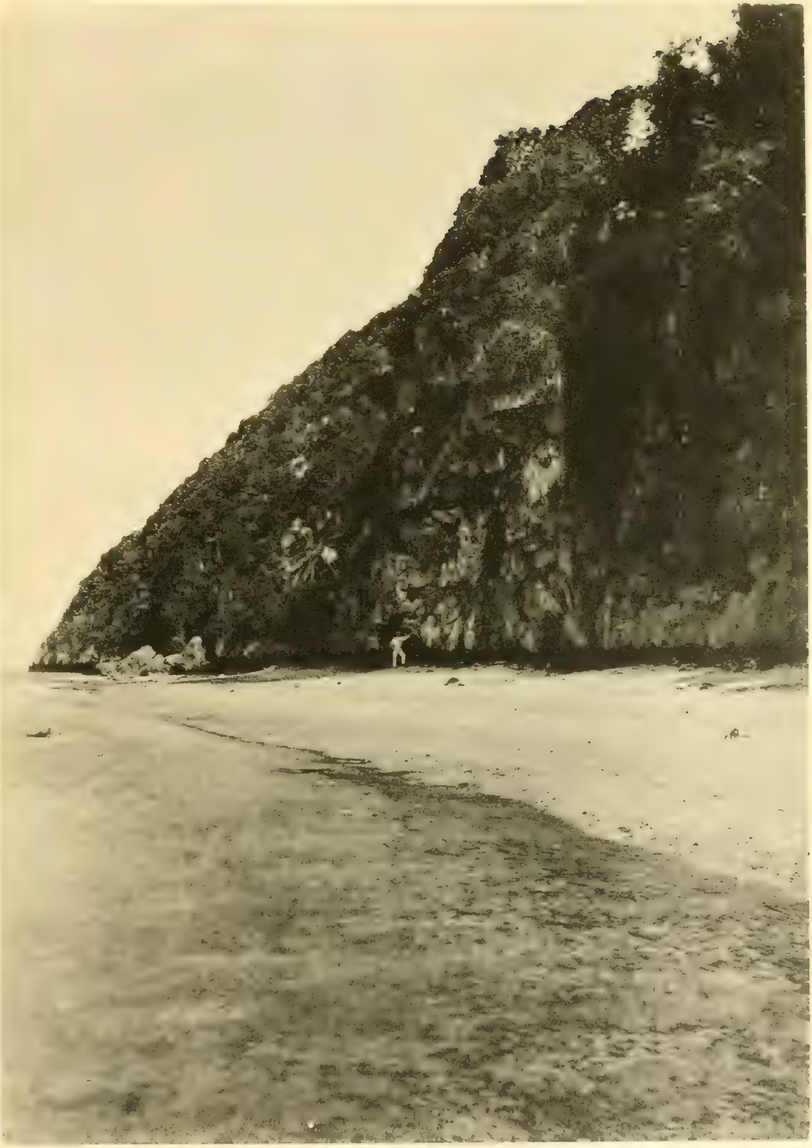
ANDREWS-FIJI. TO FACE PLATE 17.





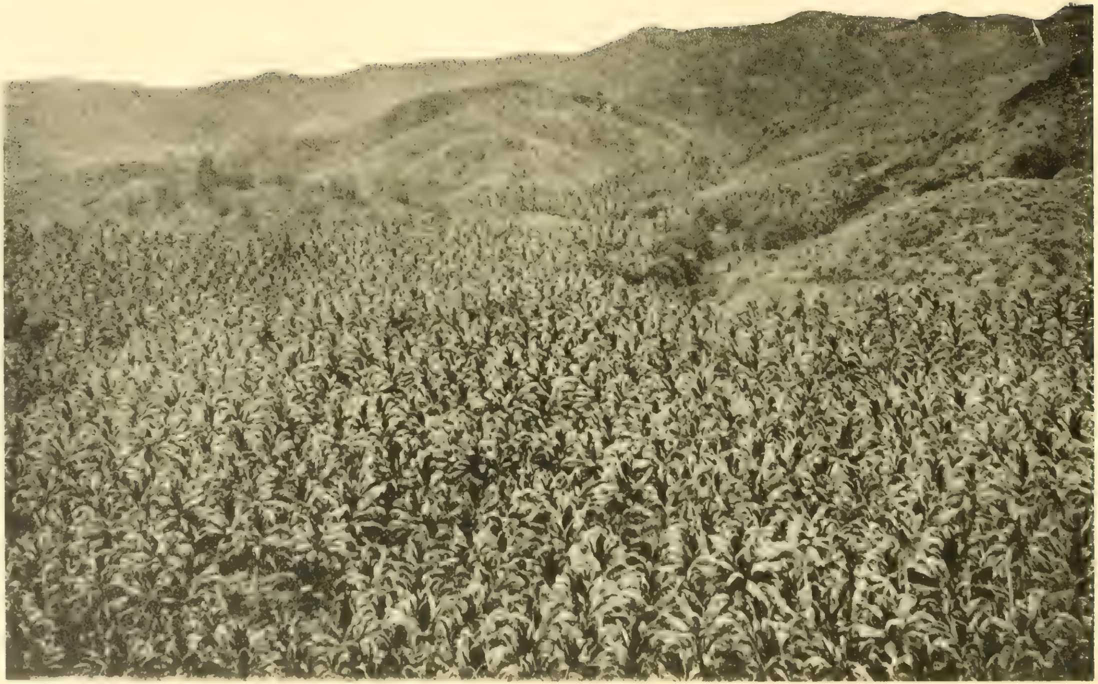
ANDREWS PHOTO THE HELIOTYPE PRINTING CO., BOSTON.

CENTRAL BASIN OF MANGO.



ANDREWS PHOTO. THE HELIOTYPE PRINTING CO. BOSTON.

LIMESTONES CLIFFS, THITHIA.



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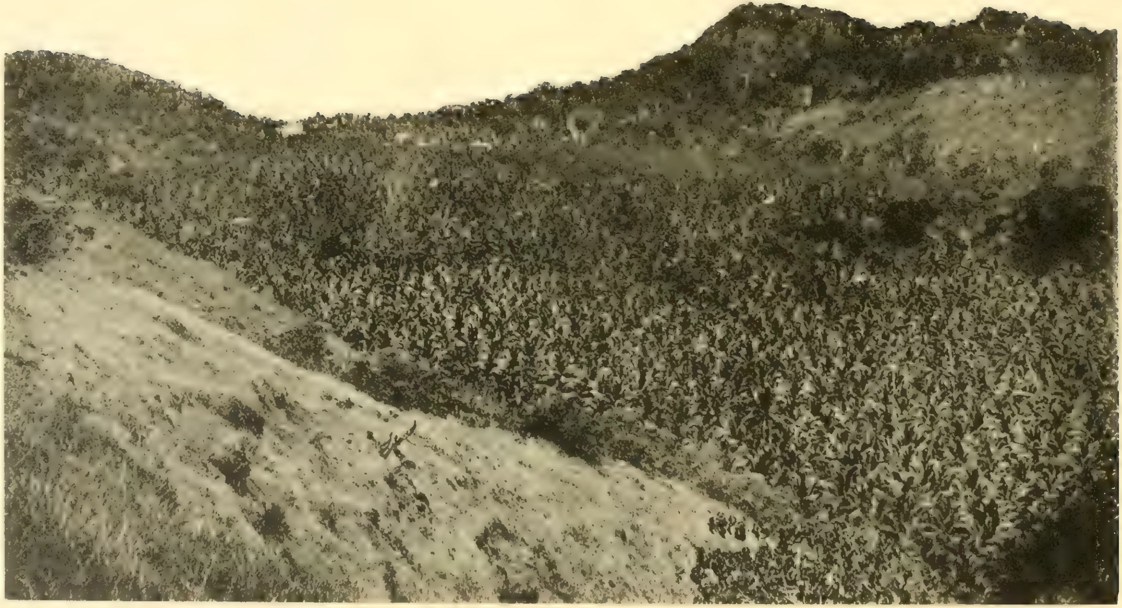
ANDESITE OUTBURST, THITHIA.



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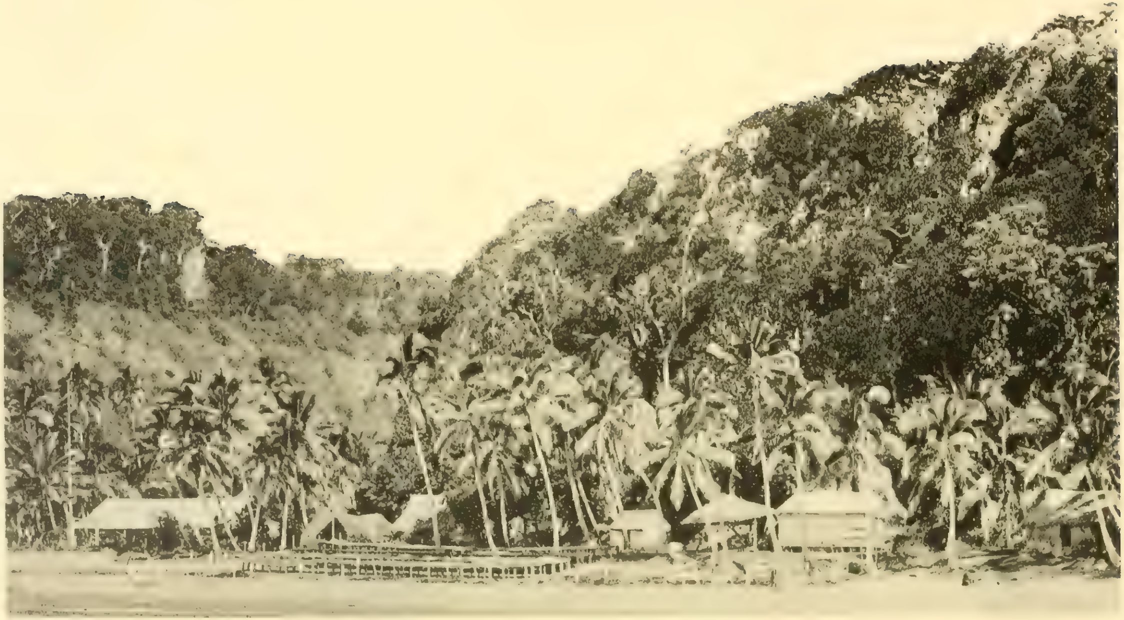
OLD LAGOON OUTLET, THITHIA

PLATE 21.



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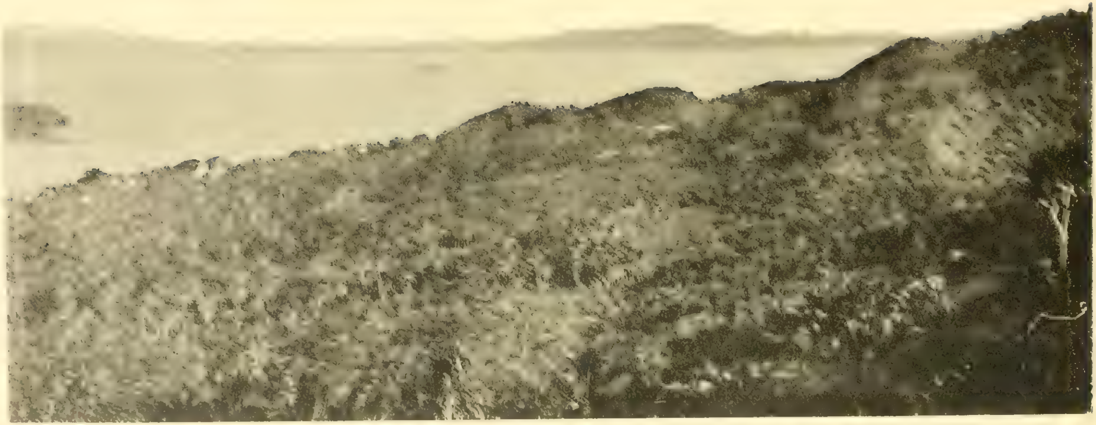
OLD GAP, THITHIA



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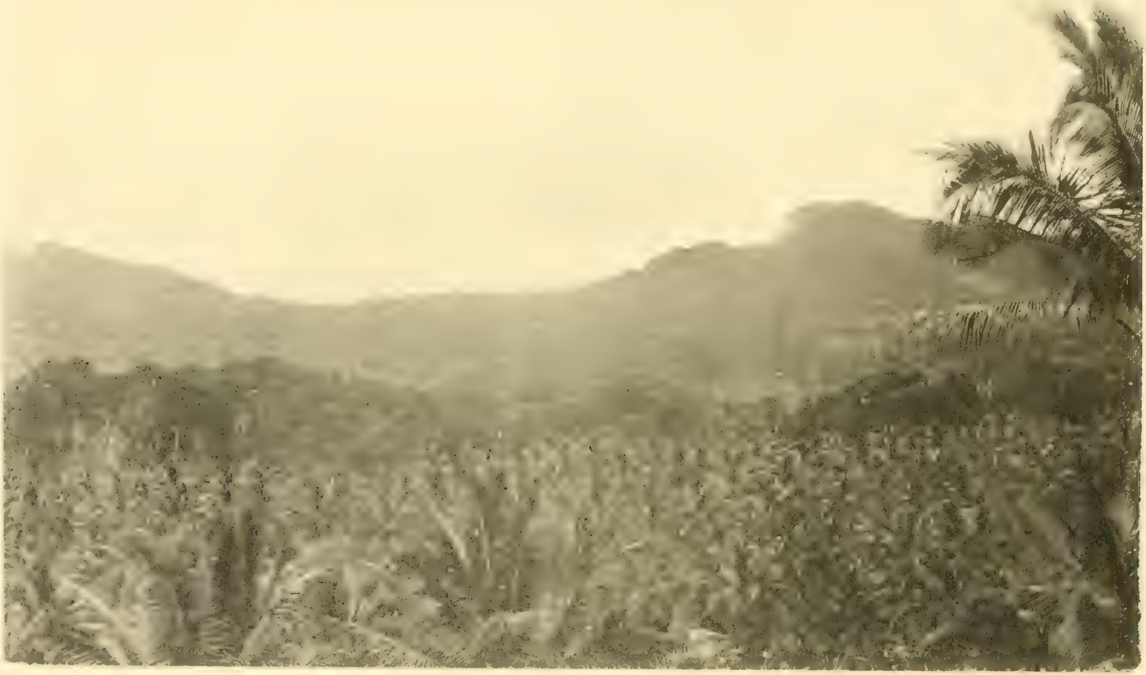
PART OF LAGOON, VANUA MBALAVU.



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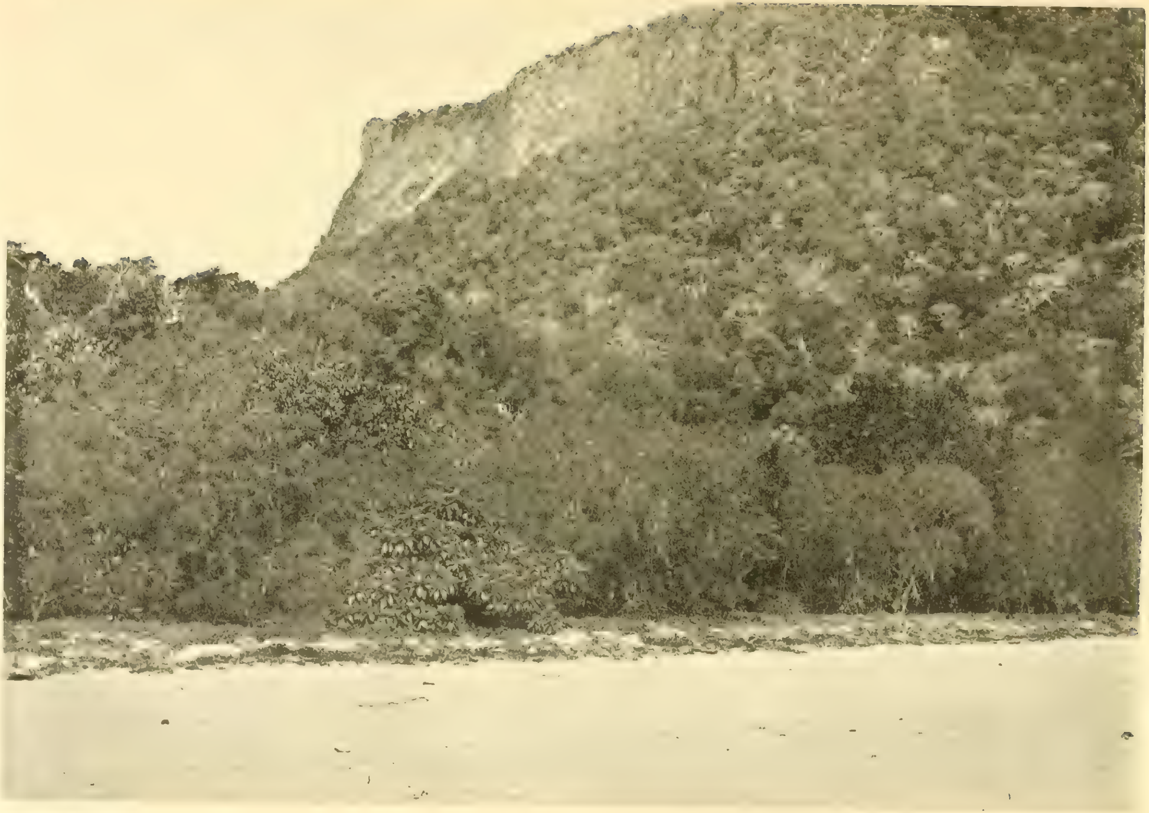
CENTRAL HOLLOW OF NAITAMBA.



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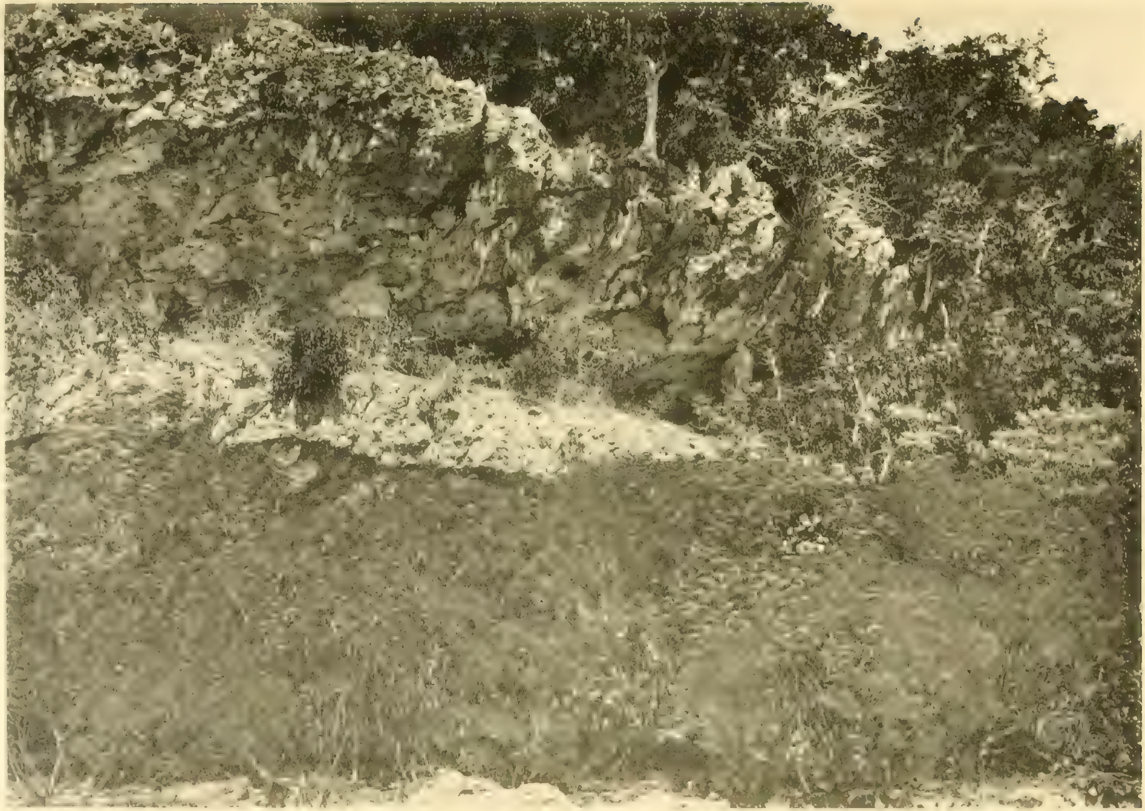
VATU VARA



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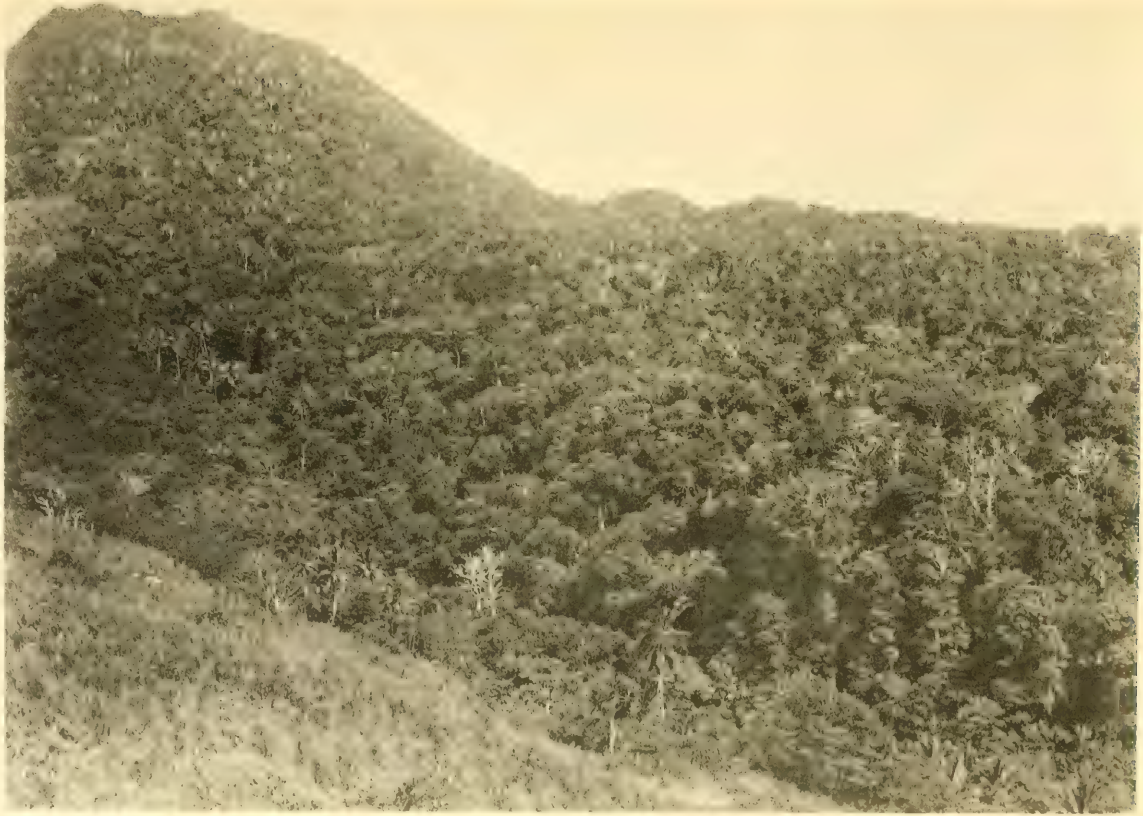
LINES OF MARINE EROSION, VATU VARA.



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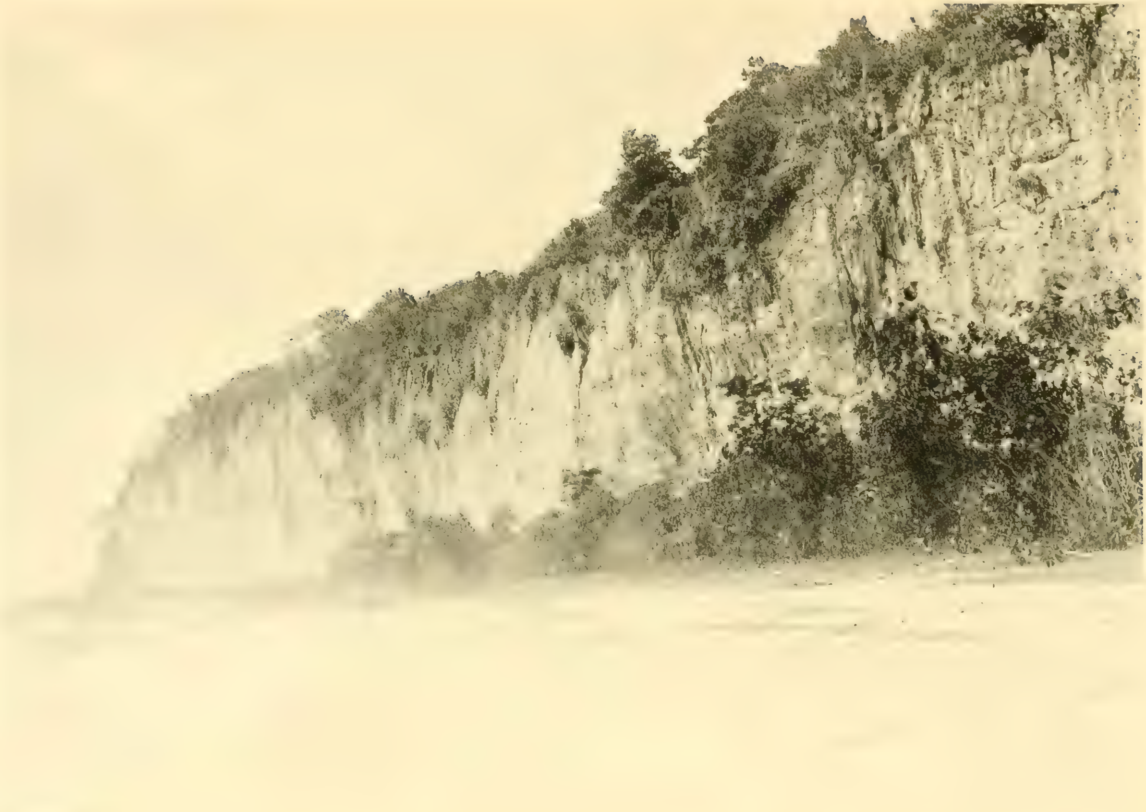
SUMMIT OF YATHATA



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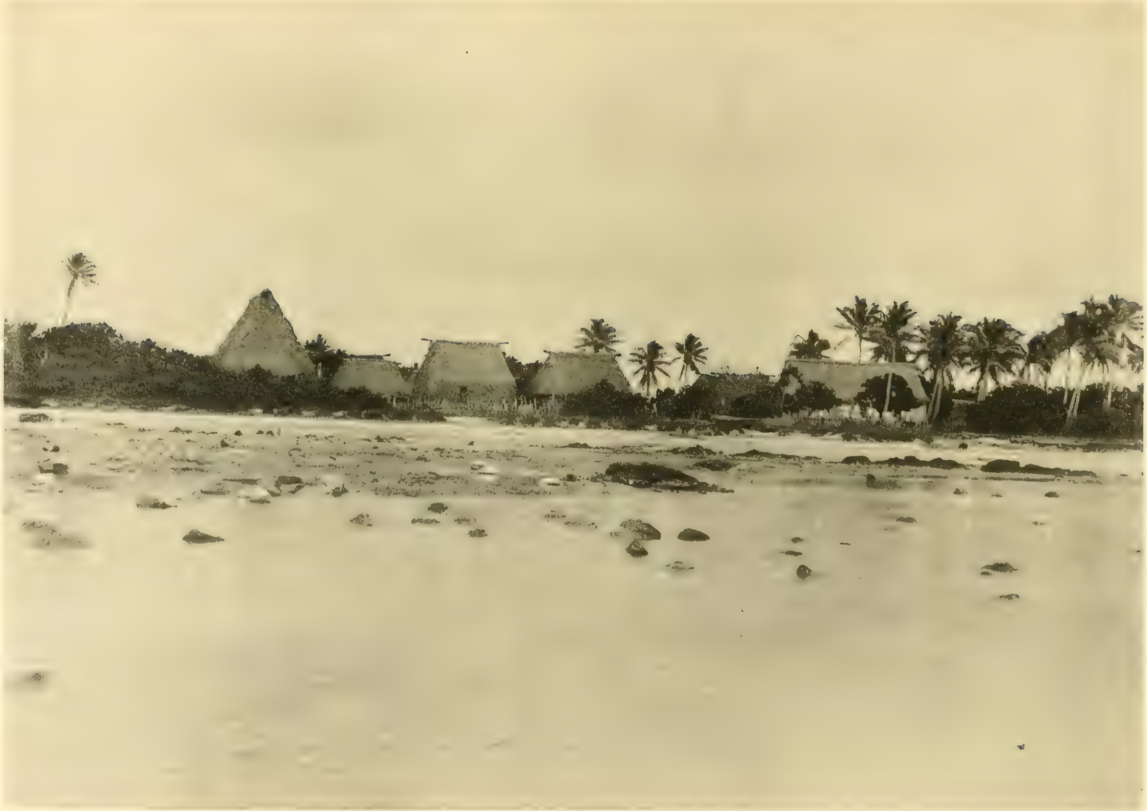
THE HELIOTYPE PRINTING CO., BOSTON

CLIFF, WEST COAST OF VATU LEILE.



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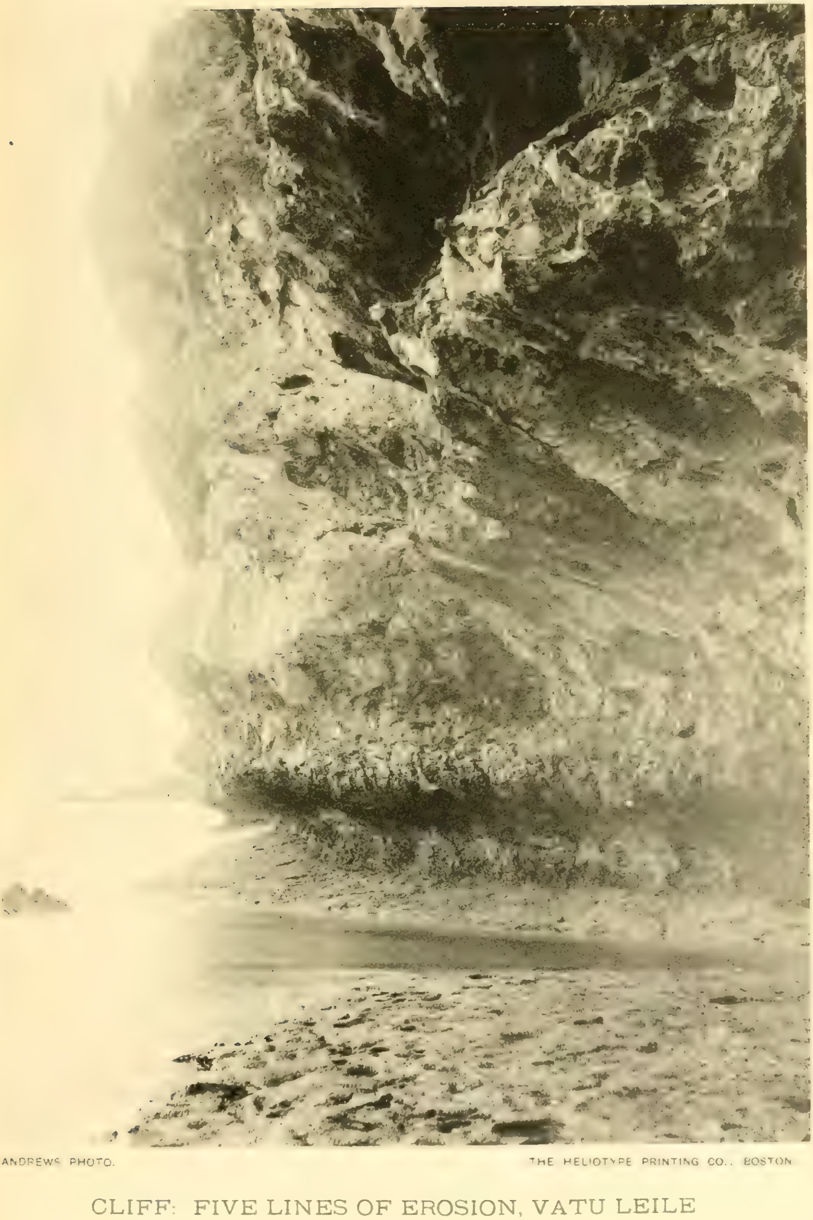
EAST COAST OF VATU LEILE



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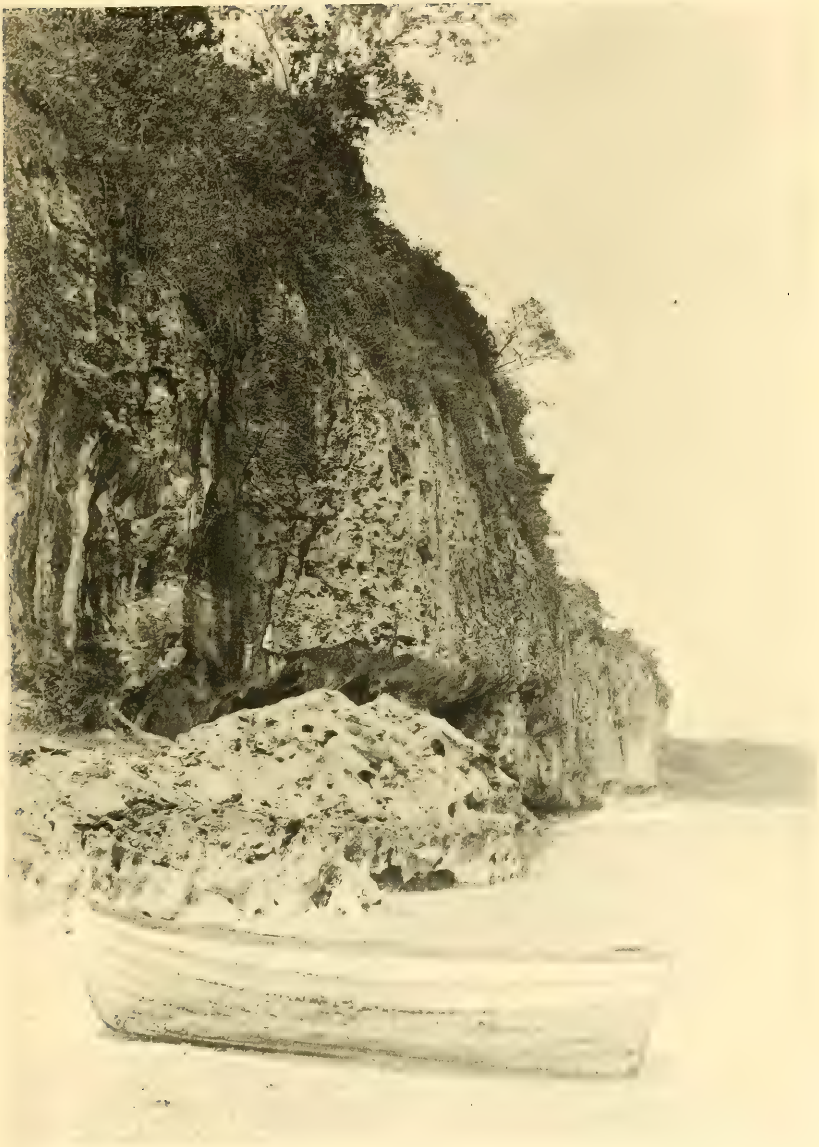
CLIFF: FIVE LINES OF EROSION, VATU LEILE



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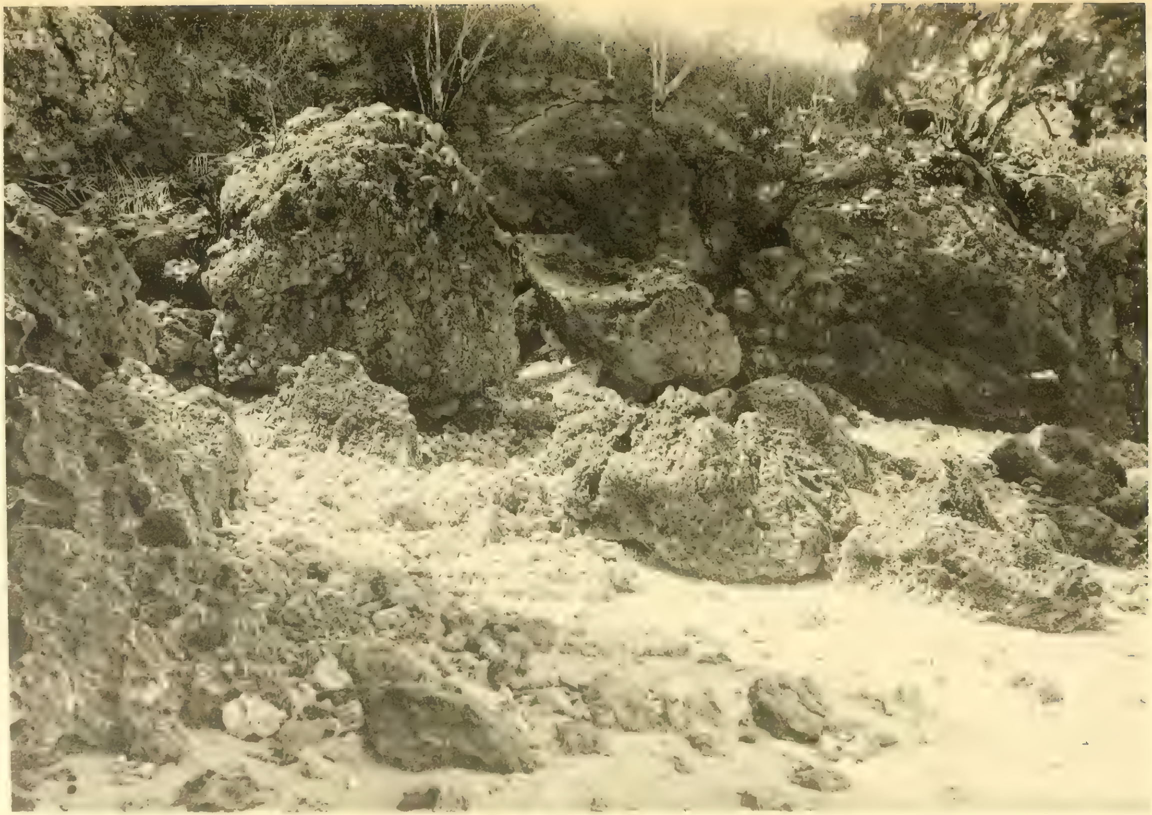
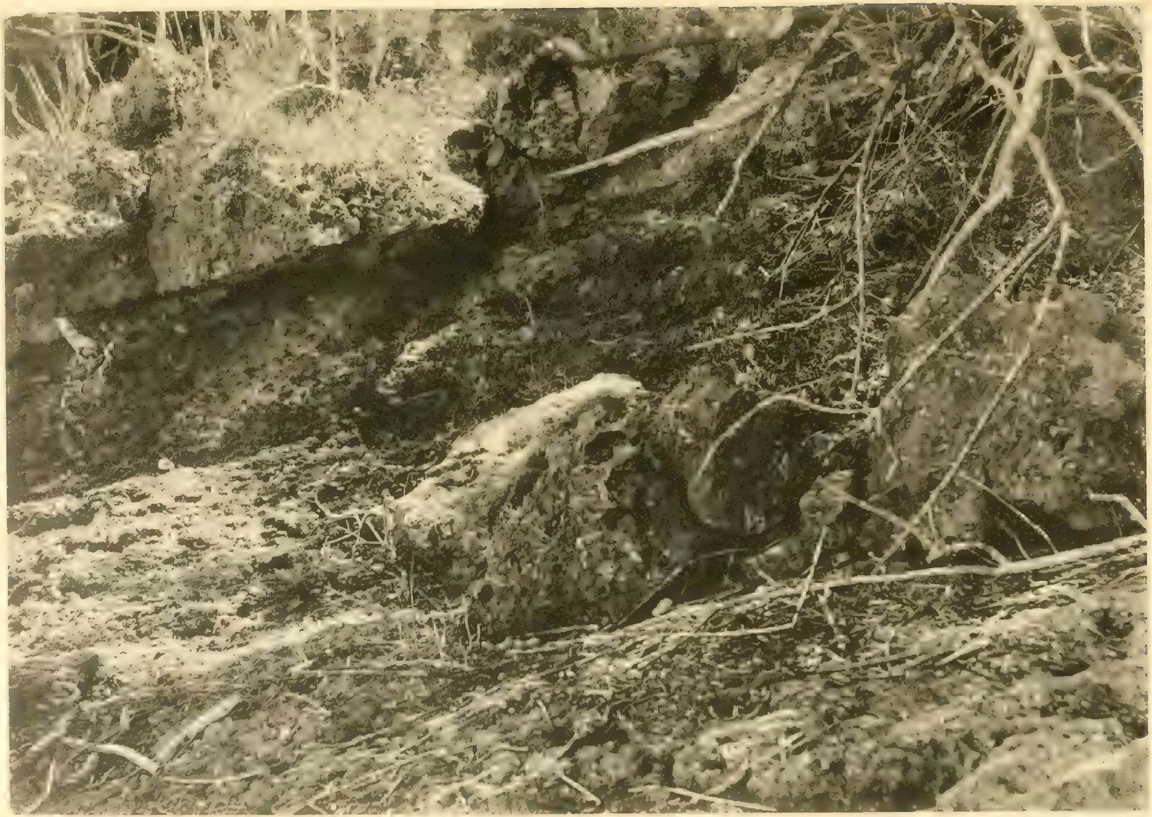
THE HELIOTYPE PRINTING CO., BOSTON.

CLIFF, VATU LEILE.



JUNCTION OF RAISED REEF AND BEDDED LIMESTONES, THUVU-SINGATOKA BEACH



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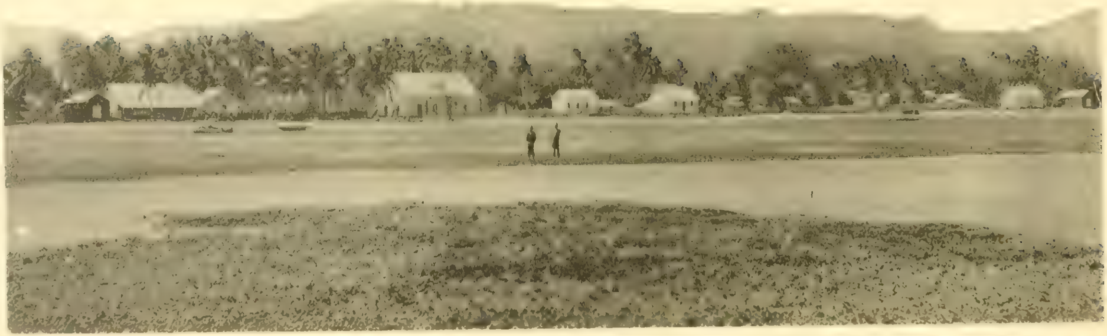
STRATIFIED LIMESTONES, THUVU-SINGATOKA BEACH



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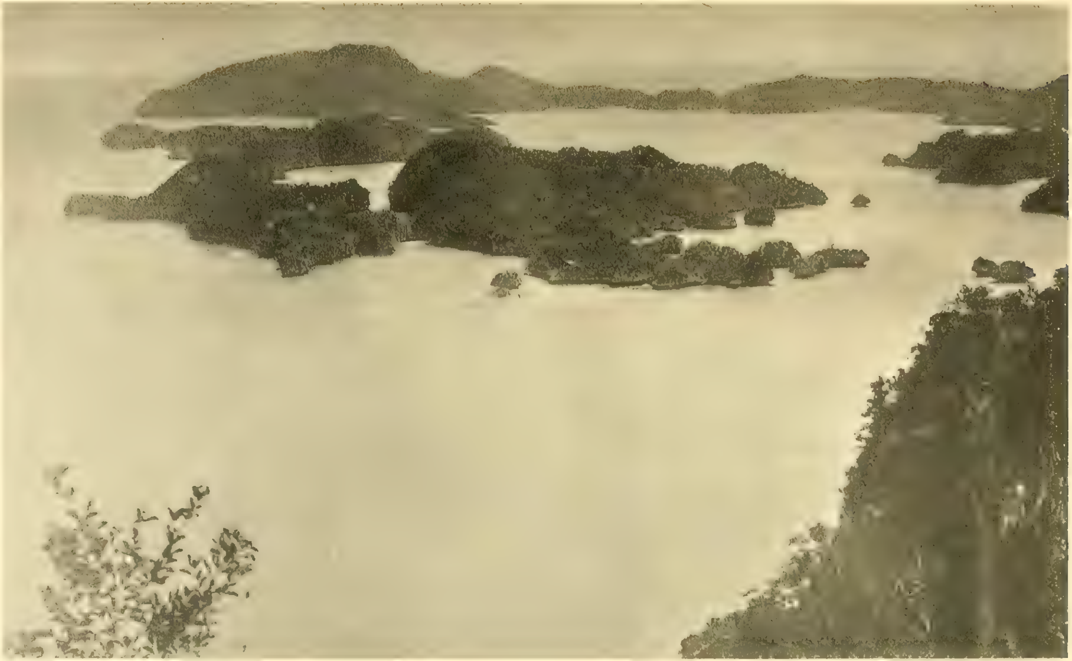
ANDESITE BUTS, LAKEMBA



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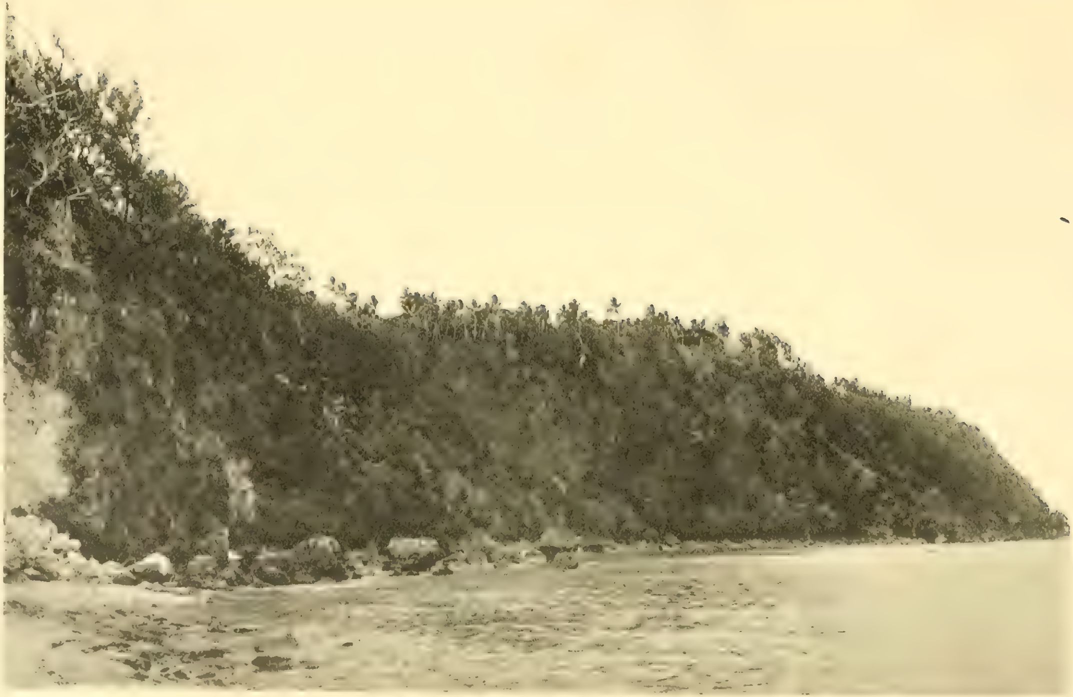
NGILLANGILLAH AND BAY OF ISLANDS.



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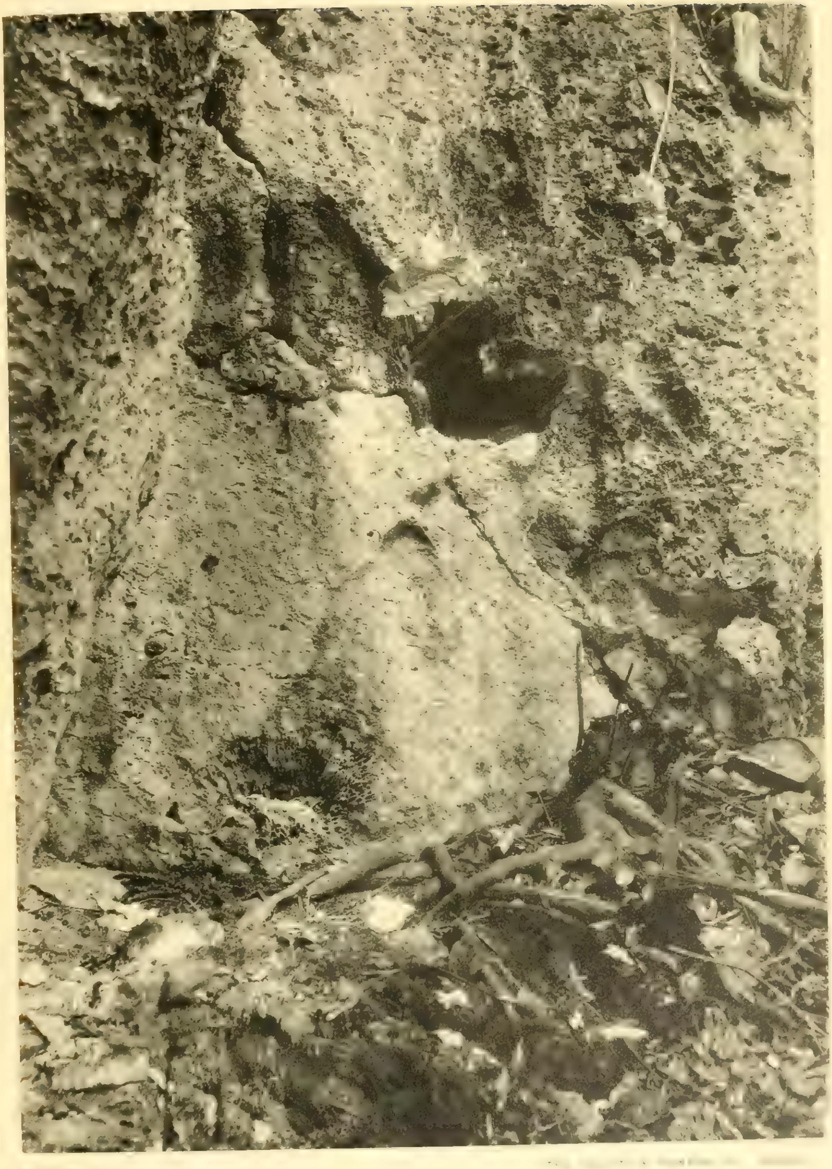
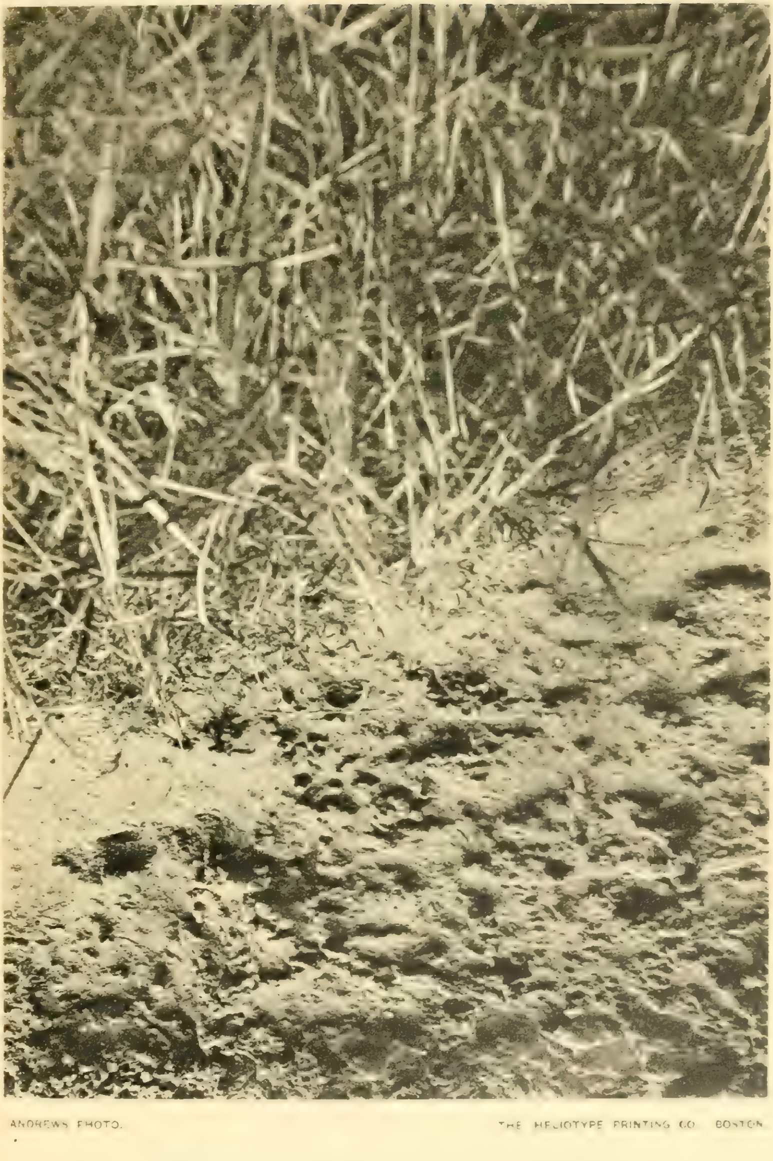
LIKU, VAVAU, TONGA ISLANDS



CLIFF, MANGO



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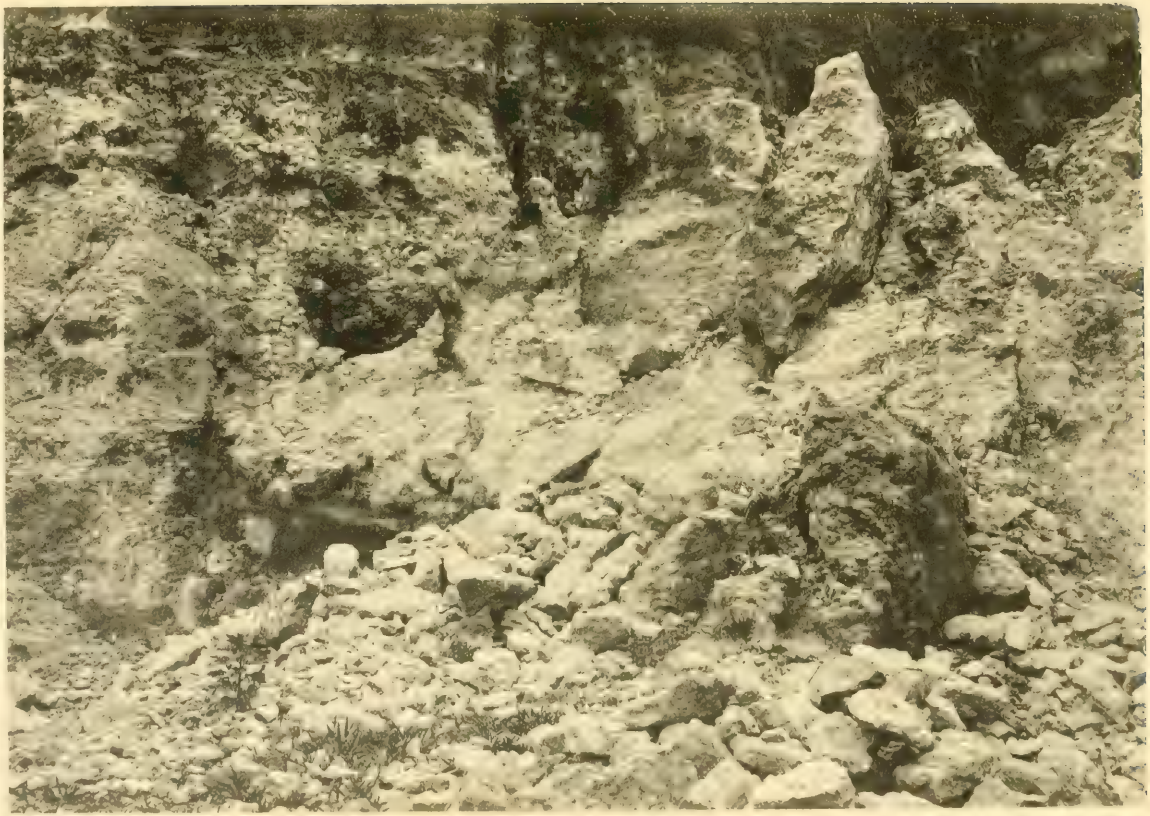
SOFT CLIFF FACE. SINATOKA RIVER.



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QUARRY, WALU BAY.

The following Publications of the Museum of Comparative Zoölogy are in preparation: —

Reports on the Results of Dredging Operations in 1877, 1878, 1879, and 1880, in charge of ALEXANDER AGASSIZ, by the U. S. Coast Survey Steamer "Blake," as follows: —

E. EHLERS. The Annelids of the "Blake."
C. HARTLAUB. The Comatulæ of the "Blake," with 15 Plates.
H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea of the "Blake."
A. E. VERRILL. The Alcyonaria of the "Blake."

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of ALEXANDER AGASSIZ, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

Illustrations of North American MARINE INVERTEBRATES, from Drawings by BURKHARDT, SONREL, and A. AGASSIZ, prepared under the direction of L. AGASSIZ.

LOUIS CABOT. Immature State of the Odonata, Part IV.
E. L. MARK. Studies on Lepidosteus, continued.
" On Arachnactis.
R. T. HILL. On the Geology of the Windward Islands.
W. McM. WOODWORTH. On the Bololo or Palolo of Fiji and Samoa.
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AGASSIZ and WHITMAN. Pelagic Fishes Part II., with 14 Plates.

Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieutenant Commander Z. L. TANNER, U. S. N., Commanding, in charge of ALEXANDER AGASSIZ, as follows: —

A. AGASSIZ. The Pelagic Fauna.
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OF THE

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AT HARVARD COLLEGE.

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Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieut. Commander Z. L. Tanner, U. S. N., Commanding, in charge of Alexander Agassiz.

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Bulletin of the Museum of Comparative Zoölogy

AT HARVARD COLLEGE.

VOL. XXXVIII.

GEOLOGICAL SERIES, Vol. V. No. 2.

THE STRUCTURAL RELATIONS OF THE AMYGDALOIDAL MELAPHYR IN BROOKLINE, NEWTON, AND BRIGHTON, MASS.

BY HENRY T. BURR.

WITH TWO PLATES.

CAMBRIDGE, MASS., U. S. A.:
PRINTED FOR THE MUSEUM.
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No. 2. — *The Structural Relations of the Amygdaloidal Melaphyr in Brookline, Newton, and Brighton, Mass.* By Henry T. Burr.

The sedimentary rocks of Boston and vicinity are associated with basic igneous rocks of various ages. Local geologists are accustomed to divide these, roughly, into two broad groups, — the trap dikes and the "melaphyrs" or "amygdaloids." The latter are the greater masses, irregular in outline and much altered in structure and texture. The former are distinctly dikes. They still retain much of their original crystalline texture and are unaffected by cleavage.

While there is seldom any difficulty in distinguishing the two types in the field, it is not easy to define the points of difference. Under the microscope the melaphyr is excessively decomposed. It has been studied in the Brighton area by E. R. Benton ('**80**, p. 416), at Hough's Neck, Quincy, by J. E. Wolff ('**82**, p. 232), and by T. G. White ('**97**, p. 140). These writers agree in describing the rock as an altered basalt. It is made up, typically, of plagioclase feldspar, magnetite, epidote, and a mass of calcite, chlorite and other more or less indeterminate alteration products. I have nothing to add to this save that slides from various portions of Newton and Brookline exhibit the same general characters. The traps are likewise much decomposed, although in varying degrees. Dr. T. A. Jaggar, Jr., in investigations not yet published, has found that many of these are altered basalts. There seems to be no means of distinguishing them, petrographically, from the melaphyr.

Macroscopically, the extent of alteration in the melaphyr is usually sufficient to obliterate the crystalline texture. The traps almost invariably appear, to the eye, crystalline. The melaphyr has generally assumed a greenish to purplish tinge, difficult to describe, but quite characteristic. The melaphyr is frequently amygdaloidal. The amygdules have a peculiar habit of grouping themselves about centres. They are seldom scattered uniformly through any considerable mass of the rock. The traps are seldom amygdaloidal, and the amygdules, where they occur, tend to be rather sparsely disseminated.

The traps have the form of fairly regular dikes and sills. Even the earliest of these gives evidence of having followed joint cracks more or less perfectly developed. The melaphyr, on the other hand, where it has come into igneous contact with the sediments, has torn its way through without regard for their structures. It cannot be doubted that portions of the sediments, at least, were but slightly consolidated at the time that the igneous mass was forced into them. The melaphyr shows evidence of having undergone nearly the same structural changes as the rocks with which it is associated. It is cleaved, in many places, quite as perfectly as the slates and conglomerates. It is cut by the same joint systems. There is evidence for believing it to have been tilted to somewhat the same extent as the associated sediments.

The melaphyr bears many inclusions of felsite[1] and of slate. In many cases these appear to have been partially fused, sometimes to the point of becoming intimately mixed with the melaphyr itself. These inclusions are highly characteristic of this rock.

Melaphyr occurs, within the limits of the so-called Boston Basin, at Nantasket, in Hingham, on Hough's Neck, Quincy, on the Neponset River south of Mattapan, at Needham, and in Brookline, Newton, and Brighton. It is with the latter area that this paper deals.

The melaphyr, although so much altered internally, is yet a fairly resistant rock. It usually stands out in prominent ridges and is thus readily traced. If it were known to be associated with a definite horizon, it would be extremely useful in deciphering the very involved structure of the region. Professor Crosby ('89, p. 10), and others who have worked with him have regarded these rocks as contemporaneous flows, occurring at or near the base of the conglomerate series. If such were the case, the melaphyr would have a value as an horizon marker. The evidence in the Brookline, Newton, and Brighton areas seems to indicate that the melaphyr is intrusive into the conglomerate and even into the overlying slate. If such is the case, it is not associated with a definite horizon and thus loses the greater part of its value as a guide to the structure.

The evidence to be presented is of three kinds: (1) The sediments which appear to overlie the melaphyr do not contain fragments of it; (2) The contacts, wherever observed, are of igneous character; (3) The melaphyr masses do not show that structural accordance with the sediments which would be demanded of them as flows.

---

[1] The ancient rhyolitic rocks of this region are known, locally, as felsites. It is in this sense that the term is used in this paper.

1. THE LACK OF MELAPHYR PEBBLES IN THE CONGLOMERATE. — The melaphyr appears to be overlain by a considerable thickness of heavy conglomerate. This is particularly true of that in the Brookline area, where it occupies the centre of an anticline and is surrounded by the coarse basal beds of the conglomerate, dipping away from it in all directions. Heavy sediments, such as these, must have been deposited in shallow water, within the zone of wave action. It is not easy to see how they could have been formed without including some fragments of the underlying rock. With this in view the conglomerate has been carefully examined. Few pebbles of basic character have been found, none referable to the melaphyr.[1] Such evidence is of negative character, and is, therefore, not conclusive, but it has some considerable value.

2. EVIDENCE FROM CONTACTS. — The zone of contact between the melaphyr and the sediments is evidently a zone of weakness, for its place is generally occupied by swamps and other low places. Actual contacts are, therefore, not often seen. On Newton Street, Brookline, (Plate 2, Loc. 1), nearly opposite the end of South Street, is an irregular mass or tongue of melaphyr nearly surrounded by conglomerate. This mass cannot be traced far in any direction, but is presumably connected in some way with the main melaphyr mass to the west. It is seen in contact with the conglomerate at several points. It cuts the latter in a very irregular way, and without regard for bedding or structure. It is certainly not a flow nor even an intrusive sheet. It is best regarded as an irregular tongue or offshoot from the main melaphyr mass. The rock at this point is the typical melaphyr and is not to be confounded with the later traps.

Farther westward, on the south side of Brookline Street (Plate 2, Loc. 2), the melaphyr is again exposed in contact with conglomerate. The melaphyr at this point is not over one hundred feet wide and is flanked by conglomerate on both sides. The only contacts exposed are on the northern side of the melaphyr. This would be the lower side if the rock represented a flow. This contact is unmistakably igneous. The hard sediment has been fused, in contact with the igneous rock, to an homogeneous red mass which has the appearance of felsite. It is unfortunate that the southern contact is not shown. It is, however, hardly possible that the melaphyr can be a flow, for it cuts the sediments vertically while the latter have a prevailingly gentle dip to the south. Still farther west, on the north side of Nahanton Street (Plate **2**, Loc. 3), conglomerate occurs in a re-entrant angle between outcrops of melaphyr. No actual contact is seen, but a large boulder, found near to this conglomerate outcrop, shows both conglomerate and melaphyr, the contact being apparently igneous.

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[1] Professor Crosby ('89, p. 10), however, states that the conglomerate contains fragments of the melaphyr.

No other contacts are known on the southern border of the melaphyr area. On the northern border contacts have been seen in but one locality. East of Hammond Street (Plate **2**, Loc. 4), opposite the cemetery, the melaphyr has been exposed in two trenches. In both cases it is in contact with conglomerate on its southern side. The contact is practically vertical, while the conglomerate dips north at a moderate angle. A red zone is developed in the conglomerate along the contact, and the sediment is penetrated by little tongues of the melaphyr. The north side of the melaphyr is not shown. It seems reasonable to regard this small body as an offshoot from the main mass to the south. The deeper of the two trenches is now filled, while the sides of the other have fallen in, obscuring the evidence. The main mass of melaphyr in this area is separated from the conglomerate by a belt of low land. A ditch has been dug along this belt from Hammond Street to Heath Street. At present there is no exposure of rock in this ditch, but the débris taken from it has been piled along its banks. A number of fragments have been found in this débris which show the melaphyr in contact with the conglomerate. Several of these bear witness to the igneous nature of the contact, and one, in particular, shows the sediment penetrated by a tongue of the melaphyr. In the same specimen a stringer from the sediment has been partially fused and included within the igneous rock. Under the microscope the feldspars are seen oriented in striking conformity with the boundaries of this included fragment.

The melaphyr is seen in contact with the conglomerate in several places on the bank of the Charles River north of Boylston Street, Newton Upper Falls (Plate **2**, Loc. 5). It clearly penetrates the sediment along the contacts. In two places it cuts, dike-like, across the bedding of the conglomerate. Farther east, on Rockland Street (Plate **2**, Loc. 6), the two rocks appear together, the contact zone developed by the melaphyr being quite evident. On the corner of Rockland Avenue and Boylston Street the melaphyr, although not seen in direct contact with the sediments, is filled with fragments of sandstone, presumably derived from the neighboring sedimentary rocks (Plate **2**, Loc. 7).

On the north side of Commonwealth Avenue, a little east of Auburndale (Plate **2**, Loc. 12), a ledge of coarse sandstone is cut by several irregular, dike-like intrusions of the melaphyr. The two rocks look much alike upon the weathered surface, so that it is difficult to differentiate them in the outcrop. The main body of melaphyr does not appear in contact with the sandstone, but is to be seen in an outcrop fifty yards eastward. A half-mile farther east, on the corner of Prince Street (Plate **2**, Loc. 13), the melaphyr is in contact with similar sandstone. The contact is unmistakably igneous. The sandstone dips north at an angle of 15°. The plane of contact also dips north, but at a much higher angle, approximating 50°. The effect of the igneous rocks upon the sandstone is plainly visible. Structures are obliterated and a distinct contact zone is developed, while the irregularity of the contact is such as could hardly be produced except by igneous action. Under the microscope the feldspars are seen to be aligned along the contact.

The melaphyr is not again seen in contact with sediments for three miles toward the east. On Cambridge Street, Brighton, a short distance west of Foster Street, a cliff of sandstone and conglomerate is capped by melaphyr. The contact shows abundant signs of igneous action. This would, however, be true if the melaphyr were a flow. In the Allston area, bounded approximately by Cambridge and Warren Streets and Commonwealth and Harvard Avenues, contact exposures are fairly numerous and frequently satisfactory. The relations of the rocks in this area have been discussed by several writers, notably W. O. Crosby, E. R. Benton, and H. G. Woodward. Benton concludes that the melaphyr is intrusive into the sediments. Crosby and Woodward do not accept this conclusion, their idea being that the melaphyr masses are made up of successive flows. Woodward has mapped the area with great care, and has differentiated six flows. His work has not been published, and is, therefore, not subject to criticism. His map, however, was printed and distributed by Professor Crosby in connection with a course of lectures given at the Boston Society of Natural History in 1889–90. As this map shows very clearly the location of the six supposed flows, it seems fair to discuss them, not forgetting that Woodward may have been in possession of evidence which has escaped the writer.

The most southerly of these supposed flows is not well indicated in the field. It is not seen in contact with the sedimentary rocks. The second "flow" is indicated by three outcrops. One of these, lying north of the elbow in Commonwealth Avenue, shows amygdaloidal melaphyr overlain by patches of sandstone and slate. The contact is not striking, as the melaphyr and the sandstone are of the same dull green color, and not unlike in texture. It becomes clear, however, on examination, that the melaphyr has been forced into the sediment. Fragments of the latter have been torn off and lie embedded in the melaphyr. In places the igneous rock breaks across the bedding planes, occasionally developing a contact zone, within which the bedding is obliterated and the sediment hardened.

The third "flow" is marked by a very irregular ridge of melaphyr, extending, with a few interruptions, from Commonwealth Avenue across Allston Street to Cambridge Street. Contacts with the slate are shown in several places. The lower or southerly contacts need not be discussed. Whatever the relations of the melaphyr may be, those contacts would necessarily be igneous. Contacts on the northern or upper side are to be seen at the so-called carriage-house quarry on Allston Street (Plate **2**, Loc. 15), on the edge of the woods, two hundred yards north of the elbow in Commonwealth Avenue, and in several exposures along the northern face of the ridge at the end of Allston Heights (Plate **2**, Loc. 16).

The slate at the carriage-house quarry (Plate **2**, Loc. 10) is seen lying on the back of the melaphyr ridge. It is tilted at a high angle, dipping north 40°–60°. It is warped as though powerfully twisted. The melaphyr just below the contact is full of slate fragments which are twisted and gnarled as though they had writhed under the influence of the molten mass. The actual contact is irregular. Tongues of the melaphyr penetrate the slate, cutting the bedding, while the contact zone is marked by a deep red band, varying from a sixteenth to a quarter of an inch in thickness. Under the microscope the slate is seen (Plate **1**, Figure 1) to be penetrated by numberless tongues of the melaphyr, the bedding is cut and twisted, and little molten particles of the slate fill the mass of the igneous rock. The feldspar crystals are frequently aligned along the contact. Often the amygdules are seen clinging to the little blebby fragments of slate, suggesting that the latter may have influenced their formation. The plane of contact does not lie exactly in the bedding planes, but cuts them at a slight angle.

The ledges on Allston Heights show the same phenomena. The megascopic evidence is here even more striking. The slate is thoroughly filled with fine tongues of the igneous rock. Frequently the two rocks are mixed to such an extent that it is hard to say where the actual contact is. In places the slate is baked to a hornstone, blotchy with red and white, suggesting bedding lines which have become obscured in a pasty rock. Here, again, the microscopic evidence is clear (Plate **1**, Figure 2). The cutting and distorting of the bedding planes is strikingly shown.

The third exposure is intermediate between, but considerably south of, the other two. The melaphyr mass is here not more than fifteen feet thick, and is bordered by slate on both sides. The slate on the northern or upper side lies in patches on the melaphyr. Here, again, a zone of baking is developed along the contact, while the cutting of the slate by the melaphyr is quite as conspicuous as it is in the other two localities.

The two melaphyr bodies occurring next to the north make up a single ridge, or rather a succession of melaphyr knobs. Slate appears in a number of places on these knobs. These patches of slate are connected, on Mr. Woodward's map, to form a parting between the two supposed flows. A narrow, wedge-shaped mass of slate occurs at Locality 26 (Plate **2**), west of Webster Street. The melaphyr just below this slate contains fragments of it. On the contact, the influence of the igneous mass is apparent. The slate is broken by very many small faults. These do not pass into the melaphyr, the line of contact between the slate and the igneous rock being quite continuous. It is probable that these faults were produced by disturbance attendant upon the intrusion of the igneous rock, the effect being obliterated along the contact by the influence of the molten mass. A second exposure of slate occurs on this line on the west side of Webster Place. The evidence here is not so striking, but is quite as good as in the other places. A third locality appears, on Woodward's map, on Cambridge Street, behind the Convent (Plate **2**, Loc. 18). This outcrop shows, in the most conclusive manner, the extremely complicated way in which the melaphyr has been forced into the sediments. In fact, the whole outcrop is practically a breccia of great slate and sandstone blocks, held in a matrix of melaphyr, which fills all the cracks and penetrates the sediment in thousands of tongues. The sandstone blocks themselves are shattered so that they have the appearance of a fault breccia and these small displacements do not pass across the contact into the igneous rock.

Another portion of this mass is shown in contact with slate and sandstone on Cambridge Street, opposite Saunders Street (Plate **2**, Loc. 17). Recent blasting at this point makes it possible to obtain very fine hand specimens, showing the intricate way in which the melaphyr has penetrated the sediment. The fifth and sixth "flows" do not appear in contact with overlying sediments.

No other contact exposures are known, excepting several in the Allston area which are beneath the melaphyr. These would be igneous in any case. All of the known contacts, so far as they yield evidence, point toward the intrusive nature of the igneous rock.

3. Evidence from Structural Relations. — On Professor Crosby's map of the Boston area (The Geology of Eastern Massachusetts), the melaphyr is made to consist of two long arms, extending in a generally east and west direction and united in a rather broad area west of the Charles River. Each of these arms is bordered by conglomerate, and this, in turn, is rimmed with slate. Between the arms the conglomerate occupies the greater portion of the area, but is parted by a wedge of slate which broadens eastward till it encircles the two conglomerate masses, and unites with the slate areas to the north and south. This distribution would seem to lend striking support to the idea that the melaphyr is at the bottom of the series and is followed by the mass of the conglomerate with the slate at the very top. There are indicated two well-defined anticlines with melaphyr exposed in the axes and wrapping about the spoon-shaped end of the synclinal area of slate and conglomerate (see Crosby, '89, pp. 9–12[1]).

It may be assumed for the moment that this interpretation of the general structure is correct. It then becomes necessary to ascertain whether or not the distribution of the melaphyr accords with this structure. In Brookline the melaphyr occupies the middle of the southern anticline. It does not, however, appear to lie symmetrically about the felsite axis exposed in the southern part of Newton. In the considerable space between Brookline and Greenwood Streets the melaphyr does not appear. Although it is possible that it does underlie a portion of this area, the occurrence of five well-marked outcrops of conglomerate and the presence of great numbers of large conglomerate boulders makes it probable that the latter is the underlying rock. The conglomerate found on the southern side of Greenwood Street is made up almost wholly of felsitic débris. It closely resembles a conglomerate appearing near the corner of Dedham and Walnut Streets. The strike of the Greenwood Street conglomerate would carry it very near to the Dedham Street locality. It is not impossible that they are continuous beneath the intervening space. It is not at all certain that the melaphyr occurs between Greenwood Street and Newton Highlands. It is not seen in the area occupied by this anticline west of the vicinity of Dudley Street. On the south side of Central Street, west of the Charles River, red felsite is exposed within a very short distance of the conglomerate. There is not room, at this point, for the melaphyr to pass between the felsite and the conglomerate. Thus it appears that it does not completely encircle the synclinal area.

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[1] The position of these anticlinal areas is indicated, on the accompanying map (Plate 2), by heavy black lines (d d′ and e e′). These are drawn, as nearly as possible, through the middle portions of the melaphyr areas as expressed on Crosby's map. A heavy broken line (f f′) is drawn through the middle of the synclinal area of slate.

Melaphyr occurs near Newton Upper Falls, on the south bank of the reservoir, and on the Charles River north of Worcester Street. It is well exposed in three ridges on Boylston Street and Thurston Road, not far east of Upper Falls. These localities are in the middle of the synclinal belt, and trend diagonally across the supposed trend of the slate. At Crystal Lake, Newton Centre, the melaphyr again appears on the border of the slate belt. On Station Street, near Newton Centre, is a small exposure. This is nearly east of the Crystal Lake locality and possibly connected with it. It is much nearer the synclinal than the anticlinal axis.

The northern belt of melaphyr is not nearly so continuous as the southern. It does not appear to occupy an axial position. It seems, from exposures in recent ditches, that the region south of Newton Lower Falls is underlain by conglomerate and slate (Plate **2**, Loc. 23). There are excellent exposures on Chestnut Street, south of Commonwealth Avenue (Plate **2**, Loc. 24). Conglomerate appears on the shore of Chandler's Pond, near Lake Street (Plate **2**, Loc. 25). The melaphyr does not appear south of these exposures. If the limits of the conglomerate area be extended, as they should be, to include these outcrops, there will be a much greater area of conglomerate south of the melaphyr than north of it.

The distribution of the melaphyr does not, therefore, accord with the structure, as interpreted by Professor Crosby. It occurs not only in the anticlines, but in the axis of the syncline. In the northern conglomerate area it is bordered by a much greater thickness of conglomerate on the south than on the north. In the southern area it is not symmetrically arranged about the underlying felsite. It is not continuous about the synclinal area of conglomerate. This irregularity of occurrence is quite in accord with the idea that the melaphyr is intrusive.

A NEW INTERPRETATION OF THE STRUCTURE. — Before settling upon this conclusion it is necessary to consider the possibility of a different interpretation of the structure. The broad conglomerate area of Brookline, Roxbury, and Dorchester is the one well-defined structural unit in the Boston area. The conglomerate dips beneath the slates to the north and to the south and pitches eastward beneath the slates which underlie Boston Harbor. Outcrops in many parts of the area are abundant, and all accord with the idea that this belt is a broad, flat-topped anticline.

The structure of the northern conglomerate belt is not so clearly shown. On the southern side of the melaphyr in this area, the sediments dip toward it at prevailingly low angles. On Grant Avenue, Newton Centre, north of Commonwealth Avenue, the conglomerate beds are practically vertical, but in no other instance has a dip of more than 25° been seen. The average dip is probably below 20°. North of the melaphyr the dip is still toward the north, but usually at higher angles, reaching 60° to 65° on the railroad west of Newtonville. The attitude of these rocks does not suggest the anticlinal relation. It is much simpler to regard the structure as monoclinal, the dips becoming steeper toward the north.

This view is strengthened by a study of the relation which the conglomerate bears to the slate belt to the south. If the two conglomerate areas were anticlinal, the intervening slate would, of necessity, be synclinal. The conglomerate to the south appears to pass with perfect conformity beneath the slate. It is reasonably clear that the slate actually overlies this conglomerate. But the conglomerate of the northern area invariably dips away from the slate, and is everywhere discordant with it. The conglomerate dips northward at angles of from 10° to 25°. The slate dips in the same direction, but at angles varying from 5° to 90°. It is clear that there is some sort of break along this line of contact. Fortunately several exposures yield positive evidence of the nature of this break.

On the northeast bank of Chestnut Hill Reservoir (Plate **2**, Loc. 19) the slate is seen interbedded with coarser sediments and clearly overthrust by a massive bed of conglomerate. The slate dips north at about 80°, while the conglomerate above has a dip in the same direction of 30°. The occurrence of slate associated with bands of coarser sediment is suggestive of the transition zone between the slate and the conglomerate. The same conditions may be seen on the railroad near the Pumping Station and also on the track a half-mile to the eastward. It is quite possible that the thrust produced at this point a syncline which finally yielded to the strain. The attitude of the rocks at the thrust is quite in accord with this view (Fig. 1). The effect of the thrust is observable in the slate on the neck of land separating the two parts of the reservoir. The slate at this point is excessively crumpled.

For a mile west of the reservoir the slate seems to be quite lacking. It next occurs in a limited exposure on Beacon Street, a half-mile east of Newton Centre (Plate **2**, Loc. 20). Here again there is strong evidence of overthrusting. The conglomerate cuts diagonally across the slate beds, and its under surface is deeply scored in the direction of the thrust. The relations here differ from those at Chestnut Hill. The slate dips north at a very low angle, while the overlying conglomerate has a much steeper dip (Figure 2). This relation is not suggestive of synclinal structure in the slate. If a syncline was developed in the eastward extension, it is safe to say that it did not extend to this point. Farther west the slate belt, if it exists, is covered beneath the glacial deposits of Newton. It seems extremely probable that it does underlie a portion of the low land extending along the line of Beacon Street. It appears again on the east side of the Charles River. Outcrops of slate and conglomerate occur near Chestnut Street, north of Newton Upper Falls, and a considerable outcrop of slate has recently been exposed east of Newton Lower Falls, near Waban Avenue (Plate **2**, Loc. 23). In all exposures the slate is contorted and crushed, indicating that it has undergone something of the strains experienced by the rocks farther toward the east. At Newton Lower Falls a ditch has disclosed fine conglomerate (Fig. 3), such as is frequently found immediately beneath the slates. This seems to indicate that the fault was dying out toward the west, the throw not being sufficient to bring up the lower members of the conglomerate series. It is evident that the fault fades out in like

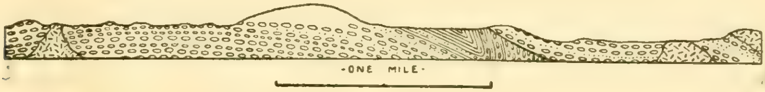

FIGURE 1. Section A A′.

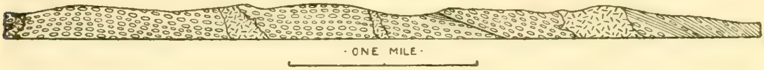

FIGURE 2. Section B B′.

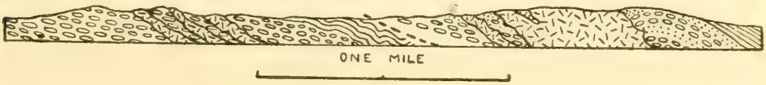

FIGURE 3. Section C C′.

manner toward the east, for the conglomerate ridges disappear, and the Chestnut Hill Slate belt apparently becomes continuous with that to the north.

That faulting of the overthrust type is to be looked for in the region is shown by the occurrence of a second thrust crossing Commonwealth Avenue at Summit Street, half a mile north of the one described (Plate **2**, Loc. 22). This is well shown in exposures on both sides of the avenue. The slate is here repeated, lying on top of the conglomerate and again overthrust by conglomerate to the north. The outcrop on the east side of the street shows particularly well the way in which the conglomerate has been crumpled by dragging on the plane of the thrust. This fault is seemingly not traceable westward. Toward the east it is complicated by a normal fault of later date.

The discontinuity of the Chestnut Hill slate belt, the actual occurrence, in two instances, of faulting on the contact between the slate and the conglomerate, the general discordance in structure between the two rocks and the known occurrence of a fault bringing about similar relations a short distance to the north, all point to the same conclusion, that the conglomerate has been thrust over the slate. All of these facts are very difficult to explain on the supposition that the conglomerate passes in a syncline beneath the slate.

The stratigraphic succession shown in this conglomerate belt is not such as to indicate anticlinal structure. South of the melaphyr the rocks are prevailingly conglomerate, coarse, as a rule, but becoming finer toward the igneous rock. Near the melaphyr sandstone bands are frequent, and there are occasional interbedded slaty layers. This is the character of the upper portion of the conglomerate in the adjacent Brookline area and quite unlike the massive beds in the lower zones. The sediments in actual contact with the melaphyr are seldom coarser than sandstone. In the eastern extremity they are prevailingly slates. Such rocks are out of place at the base of the sedimentary series, judging from the evidence elsewhere. North of the melaphyr, outcrops are few. The greater number are of slate. Thin conglomerate bands occur in a number of places in association with finer sediments. In two localities, only, are these conspicuous. A bed of conglomerate, perhaps thirty feet in thickness, is exposed on North Beacon Street, Brighton. It conforms in dip and strike to the slates on the north and on the south, and is apparently interbedded with them. Similar beds of conglomerate are known to occur within the slate series in other parts of the region. Conglomerate is exposed in a cutting near the Boston and

Albany Railroad, east of Auburndale. The dip is here 40° toward the south. As this is discordant with the dips in all neighboring exposures, it is evident that some irregularity of structure, probably a fault, has brought the conglomerate to the surface at this point. The scarcity of outcrop in this area is, in itself, nearly sufficient evidence of the small importance of the conglomerate, for this is a resistant rock and has a way of asserting itself wherever it occurs. It does not seem necessary to regard these limited exposures of conglomerate as the equivalent of the thick beds to the south of the melaphyr.

The series, reading from south to north, is made up of conglomerate, growing finer northward, interbedded sandstone and conglomerate, sandstone, and slate associated with melaphyr, slate with interbedded conglomerate, and finally a broad area of slate stretching away to the crystallines on the north. This section does not yield evidence of a repetition such as would be demanded on the supposition of an anticlinal fold.

There are no details of structure which indicate anticlinal folding about the melaphyr or synclinal about the slate. Folded strata are unknown in the region, if we except some crumpled slates on the line of the great fault. There is no changing of strikes at the eastern end of the northern belt of conglomerate, nor about the western end of the intervening slate belt. On Cedar Street, at the western end of the supposed syncline, the conglomerate maintains its generally east and west strike up to its last outcrop, within fifty feet of the melaphyr to the west.

The conclusion as to the structure is that the conglomerate of the southern area is anticlinal, and dips conformably beneath the slate of Chestnut Hill and Newton Centre, while the northern area is brought to the surface by a fault on which it has been thrust over the slate and tilted toward the north. The lower members of the conglomerate series would occur in the centre of the Brookline area and on the southern edge of the northern belt. In these places, therefore, the melaphyr would be expected to occur if it were associated with the basal rocks.

It has been stated that melaphyr does occur in the axis of the Brookline anticlinal area. No melaphyr is seen, however, on the southern edge of the northern area. The long arm which extends eastward from Newton Lower Falls is associated with rocks which are considerably above the base. The two areas of Newton Upper Falls and Newton Centre are south of the slate belt and therefore not associated with the northern conglomerate area. It is conceivable and even probable that the throw of the fault has not been sufficient to disclose the lowest beds of the conglomerate. If melaphyr were associated with these beds, it also might remain unrevealed. Even if this be true, however, the occurrence of melaphyr in association with beds higher in the series remains unaccounted for.

It appears, therefore, that neither under the former interpretation nor under that which is offered here, is the melaphyr always associated with the basal beds of the conglomerate, or, indeed, with any definite horizon. On any interpretation, the occurrence of the melaphyr in association with sediments of all kinds, from the coarse conglomerate of Brookline to the slate of Allston, is suggestive of a considerable vertical distribution.

Evidence from Structural Details. — There are some details of structure which have a bearing on the general question. At various points about the periphery of the Brookline area, small, isolated exposures of melaphyr are seen in contact with conglomerate. These do not differ, lithologically, from the larger mass. It is reasonable to suppose that they are connected with it. As the conglomerate dips away, in all directions, from the central area, it is clear that the melaphyr in these exposures is associated with sediments higher in the series than those which surround the main mass. In all cases the smaller masses are intrusive into the sediments. This suggests that the main mass also is intrusive.

The conglomerate on the north bank of the reservoir, at Newton Upper Falls, dips away from the melaphyr on the south bank. The rock walls are but a few feet apart. It is evident that the dip of the conglomerate is not sufficient to carry the lower beds exposed above the melaphyr cliff. The strike of the conglomerate varies by about 12° from the trend of the parting between the two rocks, carrying it obliquely toward the melaphyr. Conglomerate, outcropping near Eliot Station, on the Boston and Albany Railroad, strikes toward melaphyr on the opposite side of the tracks (Plate 2, Loc. 8). On Walnut Street, Newton Centre, conglomerate, on the east side of the street, strikes directly into brecciated melaphyr on the west. On the corner of Commonwealth Avenue and Valentine Street is a small exposure of conglomerate which strikes toward the melaphyr mass. In the grounds of the Golf Club, on Centre Street, slate strikes directly across the trend of the melaphyr. On Foster Street, Brighton, sandstones, on opposite sides of the melaphyr mass, strike toward each other. These occurrences indicate deformation in the sediments preceding or contemporaneous with the intrusion of the igneous rock.

On the east side of Chestnut Hill Avenue, Brighton, the conglomerate strikes N. 15° E. and dips west. On the opposite side of the street the melaphyr rises abruptly and extends westward in a prominent ridge to Foster Street and continues to Lake Street. Thus the conglomerate dips directly beneath the end of the melaphyr ridge and strikes across its trend. Considering this in connection with the attitude of the rocks on Foster Street, it seems probable that the melaphyr at this point actually cuts the sediments across their strike and is thus truly a great dike.

In the Allston area, structural discordances are many. Some of these are possibly due to faulting. In a number of instances, however, the melaphyr may be seen actually cutting the sediments. Dikes are known in the field near the bend in Commonwealth Avenue, in the woods to the north, on Cambridge Street opposite Saunders Street, and in three places in the conglomerate between Allston Street and Harvard Avenue. Two of these latter dikes are, however, doubtfully regarded as melaphyr. They have been mapped by Woodward as trap.

CONCLUSIONS. — The facts set forth in this paper are believed to lead to the following conclusions: 1. The melaphyr, in the region discussed, is intrusive into the sediments. 2. The melaphyr is not associated with any definite horizon, and is therefore of no value as a guide to the interpretation of the structure.

The first conclusion depends upon the following facts: 1. The conglomerate, associated with the melaphyr, contains no fragments of it. 2. The contacts, wherever found, are igneous in character. 3. The melaphyr is seen in contact with sediments varying from the coarsest of the conglomerate to the finest of the slate. 4. The distribution of the melaphyr shows it to be discordant with the structure of the sediments under any interpretation of the latter that has been offered. The second conclusion follows directly upon the first.

Incidentally, a new interpretation of the structure is offered for the Chestnut Hill slate belt and the northern area of conglomerate.

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EXPLANATION OF PLATES.

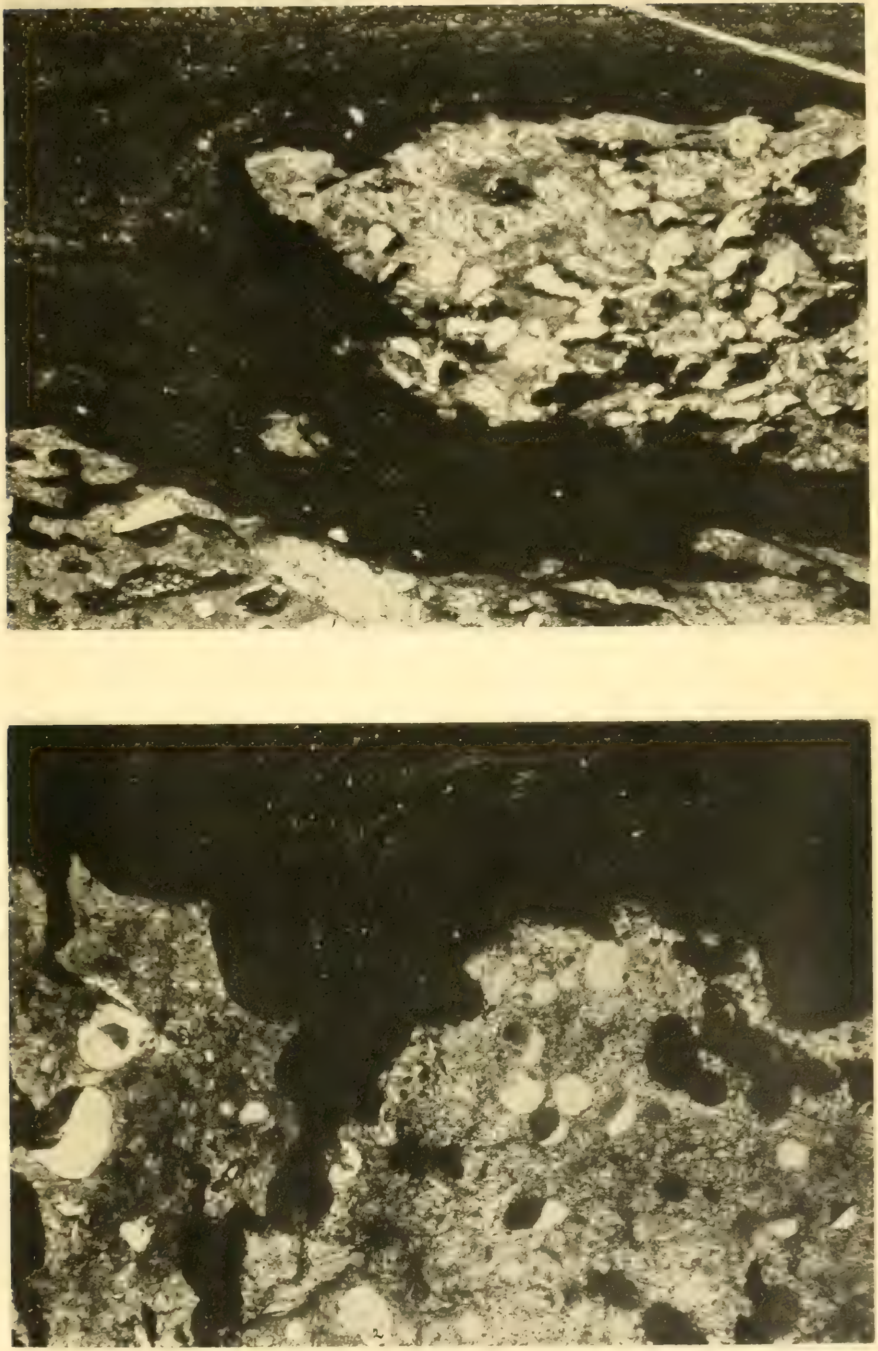
PLATE 1.

Fig. 1. Microphotograph of thin section from upper contact of melaphyr at carriage-house quarry, Allston. (Plate **2**, Loc. 15.) Shows bedding of slate cut and contorted by tongue of igneous rock.

Fig. 2. Microphotograph of thin section from upper contact of melaphyr at head of Allston Heights. (Plate **2**, Loc. 16.) Shows bedding of slate cut irregularly by igneous rock and obliterated on contact. Detached fragments and tongues of slate drawn into melaphyr.

PLATE 2.

Map of a part of Brookline, Newton, and Brighton, Mass.



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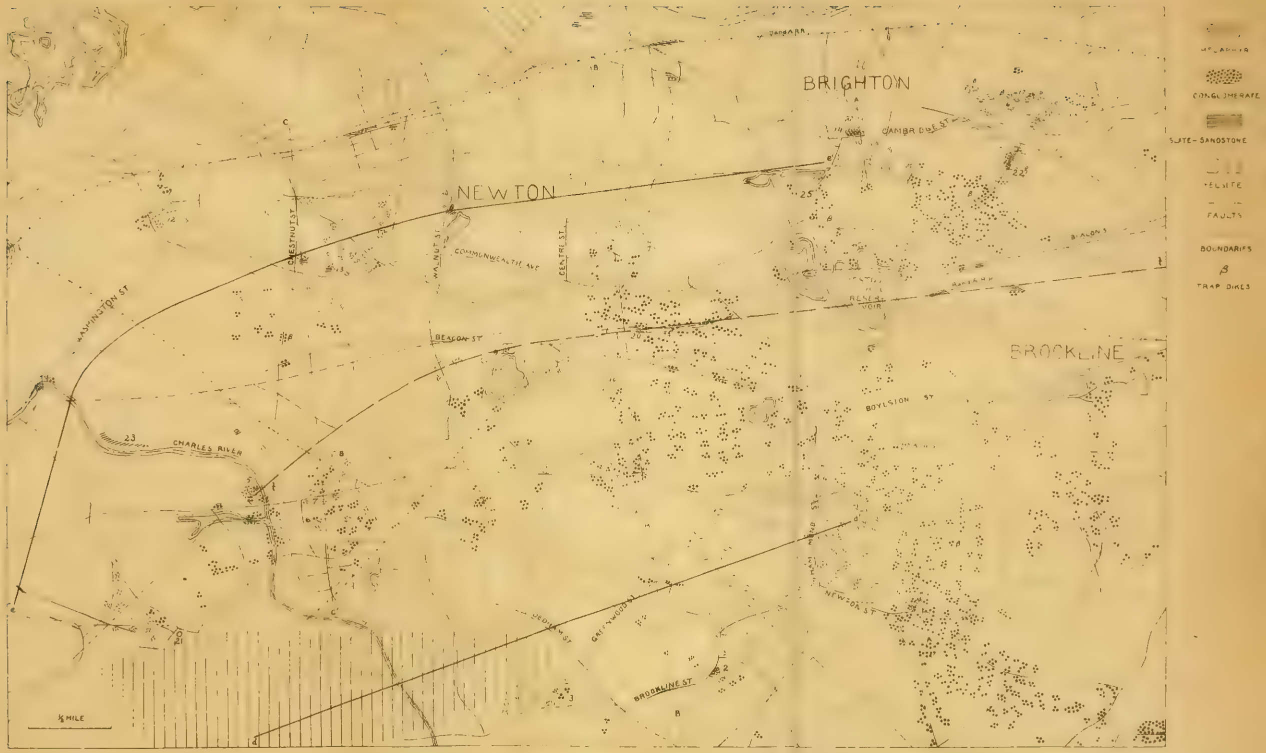
UPPER CONTACT. BRIGHTON AMYGDALOID.

Burr. Amygdaloidal Melaphyr. PLATE 2.


BRIGHTON
NEWTON
BROOKLINE
CAMBRIDGE ST
CHESTNUT ST
WALNUT ST
COMMONWEALTH AVE
CENTRE ST
WASHINGTON ST
BEACON ST
CHARLES RIVER
RESERVOIR
BOYLSTON ST
NEWTON ST
GREENWOOD ST
BROOKLINE ST
B.&A.R.R.
½ MILE
MELAPHYR
CONGLOMERATE
SLATE-SANDSTONE
FELSITE
FAULTS
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β
TRAP DIKES

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Vol. XXXVIII.

GEOLOGICAL SERIES, Vol. V. No. 3.

THE PHYSIOGRAPHY OF ACADIA.

By Reginald A. Daly.

With Eleven Plates.

CAMBRIDGE, MASS., U. S. A.:
PRINTED FOR THE MUSEUM.
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Introduction.

The results of many independent workers in the old-mountain Appalachian belt of eastern North America have shown that, as regards axial trends, formational composition, and structure, the uplands and lowlands from Georgia to Gaspé belong to one system. The unity of the whole is the result of both orogenic and epeirogenic movements; the former leading to the fairly steady accumulation of Palæozoic sediments on a subsiding sea-floor, and to the filling with Triassic sandstones of basins produced in Nova Scotia, New England, New Jersey, and Virginia during Permian warping; the latter inducing the great disorder referable to the Carboniferous "Revolution," and the simpler but important block-faulting in Jura-Cretaceous time. Besides these periods of wide-spread and pretty general mountain-building, other epochs of more local deformation were characterized by synchronous folding in limited parts of the belt. Extensive mountain-building occurred during the middle Silurian folding of Acadian and of western New England rocks, — a period of important deformation that has also been demonstrated in Virginia. More localized areas of such upturning, occurring at times not similarly occupied elsewhere, are represented by the Acadian tract which was profoundly disturbed during the late Devonian. These local foldings have, however, followed the same laws of axial development that were obeyed in the more general mountain-building, and have not interfered with the essential tectonic agreement of the system.

Thus a great generalization has been built up, in largest part by structural studies, aided, of course, by palæontological evidence, and by the lithological investigation of the sediments involved. Of late years a fourth efficient means of further developing the conception has been wrought out, simply by the recognition of the fact that sedimentation has its correlative in denudation, and that the later forms of subaerial erosion on unsubmerged areas may be expected to show similarities wherever the conditions of erosion were equivalent along the major axis of the system. The remarkable parallelism subsisting among the forms of wasted land-surfaces in New England, in the New Jersey-Pennsylvania region and in the southern Appalachians, has been broadly sketched by Davis [1] and further emphasized by Willis, Hayes, Campbell, Keith, and others. As yet the definite statement as to how far this last method of correlation may be extended to the Acadian division of the belt has not been made; in the following pages it is proposed to describe briefly and illustrate some of the more important erosion-forms in Nova Scotia and the adjacent portions of New Brunswick and to inquire into their interpretation.

The field-work on which this sketch is based was confined to a ten days' tour on the main lines and branches of the Intercolonial and Dominion Atlantic railways, supplemented by a second railroad trip from Montreal to North Sydney and a cruise close inshore from Cape Canso along the southern coast to Halifax, where the train was taken for Yarmouth. Such rapid views of the country may possibly lead to results of some value if they be checked and amplified by the study of the detailed works published by governmental survey or by private individuals.

The lack of good topographic maps of the inland areas renders the discussion difficult, and many interesting questions must on that account be left untouched. The best cartographic data are derived from the Admiralty charts of the coast-line (republished by the Hydrographic Office at Washington), from the maps of the Canadian Geological Survey so far as published, from the wall-map of Mackinlay, and from the small-scale geological map accompanying the text of Dawson's "Acadian Geology." The physiographic literature treating of Acadia is mainly concerned with glacial and post-glacial problems and with recent crustal movements. The following pages will be restricted almost entirely to the problems of bed-rock forms. The aim will be to express certain conclusions regarding the pre-glacial denudation of this region. Those conclusions do not demand an accurate knowledge of pre-glacial drainage; it is certain that the body of fact already determined will not permit of our constructing even a tolerable map of the pre-glacial river-systems.

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[1] The geological dates of origin of certain topographic forms on the Atlantic slope of the United States. Bull. Geol. Soc. America, 1891, Vol. 2, p. 545.

The Uplands.

THE SOUTHERN PLATEAU. — Rather more than three-fourths of the province of Nova Scotia (excluding Cape Breton Island) is occupied by the largest topographic unit of which I shall have to speak in detail. It may be called the "Southern Plateau." It is sharply defined in its western half by the steep front overlooking the Cornwallis-Annapolis valley, and by the ragged Atlantic shore-line; in the eastern half, the Atlantic bounds it on the south, the Truro-Pictou lowland, Northumberland Straits, and St. George's Bay on the north and northeast.

Structure. — The plateau is underlain by a complex of ancient rocks. Most of the area exhibits the outcropping edges of a very thick series of slates associated with a likewise extensive older group of quartzites; both of these series are presumed by the officers (Bailey, **'98**, p. 27 ff.) of the Canadian Geological Survey to be of Cambrian age. Van Hise (**'92**, p. 247) regards them as possibly Algonkian. Much less important from the point of view of superficial extent but significant for the unravelling of the history of the plateau, are the isolated patches of fossiliferous Upper Silurian and Devonian sediments occurring in the northern half of the long upland belt. Each of these three ancient members has been involved in the late Devonian mountain-building, which, more than any other single event, has rendered the structures of the plateau rocks complicated and difficult of interpretation. During that revolution which must have erected over the region an alpine chain of high mountains, the base of the resulting range was punctured and displaced by enormous masses of exotic granites deeply buried at that time, after the manner of granite just intruded. The Lower Carboniferous rocks afterwards deposited among the Devonian ridges in the east were, in their turn, folded, and they too compose a subordinate part of the plateau.

Form. — But all this constructional topography due to folding has been changed (Plates **1** and **2**). The geologist now directs his exploring canoe over a thousand square miles of granite moulded in the low relief of gently undulating hills separated by shallow lakes. He finds but little trace of the mountain-cover which blanketed the intrusions and permitted the slow crystallization of the vast igneous bodies. As little does he anywhere find the original surface of the ranges. There remain to him only the edges of slate or quartzite band, that once, to right, stretched up over the roof of a now vanished arch, and, to left, formed half of a ruined trough, which he can still decipher, though tattered and corrugated on its rims, the roots of an all but completely destroyed mountain mass. Throughout these fifteen thousand square miles, the observer finds no hill more than one thousand feet high, and ninety per cent of the plateau is less than six hundred feet in altitude above the sea. It will be well to note some of the readings of elevation which I have compiled from the various sources already mentioned; many of them are merely barometric determinations, but no serious error is believed to result from their use.

In addition to the fact that the coastal elevations are low, it was speedily observed that they are systematically related. At the mouth of St. Mary's Bay, the bed-rock surface of the hill-tops stands at from one hundred and fifty to two hundred feet above the sea. Thence a more rapid rise northeastwardly brings the average summit southeast of Digby to the five-hundred-foot contour, and the long escarpment of "South Mountain," running north-east by east, remains at that elevation for some sixty-five miles. Along the roughly parallel line of the Atlantic coast, the heights vary from seventy feet at Cape Sable to one hundred and fifty feet at Halifax. Profile sections taken transverse to these two belts of elevation show that there is a fairly gradual descent from one to the other, in a southeast by south direction, a descent interrupted only by local and faint reliefs to which reference will presently be made. It will be further noticed that the greater height of the hills near Halifax is related to a corresponding proximity of the Atlantic shore to "South Mountain," proving an essentially equivalent angle of slope for the surface throughout the western half of the plateau as far as the town of Digby. The same angle and direction of slope characterizes the narrow portion of the plateau south of the Truro lowland, as well as the slightly more broken northeastern third of the plateau which gradually descends from the 600–1000 foot hills on the north to the 200–300 foot hills west of Cape Canso.

The granitic "axis" of Digby and Annapolis counties rises not more than one or two hundred feet above the general surface of the broad upland, an amount insufficient to interfere seriously with the general law of a gentle southward slant for the whole plateau. But few individual hills break the even sky-line. Among these Mt. Ardoise (738 feet), southeast of Windsor, and Aspatagoen (480 feet) at Mahone's Bay, are the most prominent west of Halifax, while an unnamed summit 725 feet high lies south of Chedabucto Bay. The two last mentioned are granitic and presumably project above the plateau surface because of their comparatively great power of resistance to erosion; Mt. Ardoise also bears unmistakable evidence of having been, like the neighboring low swells of quartzite, worn out of a larger mass, although there is no direct evidence of differential hardness.

Thus the plateau is to be regarded as a single great topographic facet above which rise local cameo-like reliefs in the form of a few residual hills. It also presents the appearance of having been carved in intaglio. Sunk beneath the facet are many deep, narrow, and steep-sided valleys in the north, typified by the gorges of Bear River, Gaspereau River (Plate **3**), the upper Shubenacadie, and the East River; in the south the bed-rock valleys are shallower and have been in large part filled by drift, with the result of obscuring greatly their pre-glacial form. Bailey ('**98**, pp. 10, 11) notes the fact that they are commonly longitudinal, lying on the softer slates between the quartzite ridges. All these valleys are separated by broad interstream upland spaces and do not furnish other than quite subordinate interruptions in the relatively even plateau-top.

Is it expedient to leave, without decided emphasis in a description of Nova Scotian physiography, this remarkable, and, in view of the geological history, astonishing, flatness of the main body of the peninsula? Yet in the works already written on the subject, we read more of the inequality in the land-surface than of its essential character of low relief. "South Mountain" is spoken of as one of the two "ranges" walling in the Annapolis Valley (S. E. Dawson, '**97**, p. 155): surely a far from satisfactory designation of the escarpment of an even-topped upland. The "dominant features" of Nova Scotia "consist of ridges running parallel to the length of the peninsula" (G. M. Dawson and A.

Sutherland, '92, p. 69). In the attempt to do justice to the beauty of his native province, many a Nova Scotian has kept our facet in the background and has laid an undue amount of stress on the hilly nature of the plateau; in certain instances he has literally made "mountains out of mole-hills," apparently with the mistaken notion that the true lover of nature cannot be especially interested in her land-forms when they are subdued. Yet the marvel of Nova Scotian scenery lies in its flatness.

We have, then, to explain for this area several distinct facts: (1) The actual low relief everywhere contrasts with a former strong relief of earlier geological time. (2) The present surface is a consequence of the truncation of the outcropping edges of stratified beds of various ages and structures, — destruction of such magnitude as to lay bare certain of the vast igneous cores within the Devonian mountain-chain. The different rock-members are not only structurally diverse and chronologically distinct; they vary in hardness, although they are all absolutely resistant to the weather on account of their well advanced consolidation during the long stretches of geological time, and because of the intense crush of mountain-building. (3) Our problem is even more special than to recognize that ten thousand feet of elevation on serrate mountain-ridges has been exchanged for maximum heights of from six hundred to one thousand feet. We must also account for a general accordance of summit-levels which fall into, or nearly into, the common plane of a topographic facet gently inclined towards the south; the *fact* of this attitude is just as clear as the low absolute range of the elevations. (4) The isolated knobs, cones, and swells of bed-rock rising above the facet, and the valleys incised beneath it, must find a place in our theory of the plateau.

Fortunately, we are not here compelled to break wholly new ground in the interpretation of the Nova Scotia plateau. All will agree that it is an old mountain mass worn down to far less than its original relief. So limited, the problem resolves itself into the question as to how and when the work of denudation and the truncation of the rock-members was carried on.

Of the manner of erosion in such a region three hypotheses have been proposed; they are of unequal value, but it is advisable to note them all in this connection. The oldest of all would attribute the plain of denudation mainly to marine action during an extremely slow but very prolonged period of subsidence beneath the level of the sea. The second would regard it as a peneplain, the final product of a completed cycle of subaerial erosion, and in our case would demand a southward tilt opening a new cycle as explanatory of the present position of the peneplain.

The third hypothesis would not necessarily posit more than one cycle for the development of the existing land forms; one cycle advanced to maturity, in addition to the episode of recent drowning, would be required.

It must be confessed that we have not as yet for plains of marine erosion, criteria either so numerous or so well worked out as those for the peneplain. It has been often, and with justice, emphasized that the theory of the peneplain must recognize the fact that there is no living representative of these ancient plains of denudation. Among the many peneplains so far described, no one of them has the attitude which it should possess during and at the time of its completion ; that is, no one of them stands so near the sea-level that the relief can no longer be seriously diminished by its sluggish streams. It may be equally well advanced against the theory of marine abrasion that no *extensive* submarine plain, *proved* to be of this origin, can now be found on the flanks of the continents. In either case, explanation may be sought in the suggestion that there has been, in late Tertiary time, a special amount of epeirogenic movement. Absolute uniformity of crustal uplift and depression throughout geological time can now no more be believed in than absolute uniformity of climate or of the advance of organic life in a given region. The geological record shows that long periods of quiet have been preceded and followed by others of uneasiness and of relatively paroxysmal changes in elevation of continental masses. If the brilliant generalizations of Suess regarding wholesale Tertiary subsidence of parts of the ocean-floor are shown to be correct, particularly those referring to the North Atlantic, it is to be expected that plains of denudation of either origin would be seriously disturbed from their original position. This expectation would remain, although we might not feel complete agreement with Suess's fundamental position as regards the cause of the negative movements of sea-level. The future adjustment of geological opinion with respect to these matters may some day remove this real difficulty which adheres to either theory of the greater facets of denudation.

Both theories demand of necessity a special behavior of the earth's crust. The cycle of subaerial erosion can only be completed and a peneplain produced if there has been average crustal stability through an enormous period of time. The cycle of submarine erosion leading to the fashioning of a plain of marine denudation requires during a period at least as long a more or less steady subsidence which will permit the waves to cut inside the belt of aggraded sea-floor over which they run. This subsidence must be so slow and so long continued as to allow of the removal of alpine or subalpine relief over the region attacked by the horizontal wave-saw. The one hypothesis premises the enduring constancy of a crust at rest or with but faint oscillations of level; the other, the enduring constancy of a crust affected by tolerably steady motion in one direction.

Partly on account of this difficulty in believing in the requisite constancy of the base level during the cycle of subaerial erosion, the inquiry has been recently made by Tarr as to whether the peneplain explanation is correct when applied to the New England and New Jersey uplands; he has proposed a third theory in its stead.[1] The main idea of his thesis has been enforced in a later paper by W. S. Tangier Smith, who, however, seems to adhere to the peneplain explanation in certain cases.[2] A second objection to that explanation was founded on Tarr's criticism of the method used to account for the disturbance of the New Jersey and New England peneplains since completion. These facets are supposed, on the hypothesis of peneplanation, to have been tilted seaward, and more complex movements are believed by Hayes and Campbell to have affected the peneplained surfaces of the Southern Appalachians. In order to obviate the necessity of invoking such warpings (albeit among the simplest and commonest of crustal deformations), and to make more credible the denudational theory of the uplands in these old-mountain areas, Tarr has suggested that essentially the whole work of erosion has been accomplished in one cycle. In the mature stage of that cycle, not only are the larger streams well graded, but the slopes on the interstream spaces will be graded in sympathy with the axial profiles of the streams. The line of divide belonging to any interstream space will gently slope seaward, because the mountainous terrane will have lost more material near the sea than farther inland. On account of the greater volume of each stream near its mouth, the lower part of the valley carved by that stream will be deepened nearly to baselevel before the upstream part. Hence the valley-sides will waste faster near the mouth than toward the head-waters. Smith has strengthened this hypothesis of "beveling" by referring to the tendency at maturity toward a roughly equal spacing of master-rivers in a region even of diverse structures;[3] the result thereof being a series of divides declining to the sea at about the same rate. These would show a common sky-line when viewed from some commanding peak. Such a sky-line is supposed by Tarr and Smith to be the one mistaken in some regions for the residual profile of a finished peneplain, dissected after a new uplift. If the "beveling" hypothesis be established, it is claimed that, in such cases, we are no longer forced to believe in the repeated occurrences of land-surfaces that stood near the sea-level through the enormous period of time occupied during an old age sufficient for peneplanation. At the same time, tilting forms a superfluous supposition.

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[1] Amer. Geol., 1898, Vol. 21, p. 351.

[2] Bull. Depart. Geol. Univ. Cal., 1899, Vol. 2, p. 155.

[3] Shaler, Bull. Geol. Soc. Amer., Vol. 10, p. 263.

But, even without questioning the conclusion that downstream wasting will be so very much more rapid than upstream wasting, we may believe that the "beveling" hypothesis cannot explain the topography of the Southern Plateau. In the first place, the cross section of any of the more important interstream areas indicates a striking discontinuity of slope. Most of the sky-line profile is flat and is evidently not in the position of a graded slope where the determinant of the grade is either of the two adjacent streams. From this broad, flat upland there is on each side a sudden transition to the steep slope immediately overlooking the stream, — a sharp decline characteristic of a young valley. The frequent repetition of such an arrangement of slopes, the predominance of broad, undissected interstream facets developed indifferently on diverse rocks and structures in no sympathetic relationship with the existing stream-courses, is most simply explained by referring the land-form to two cycles. Secondly, the lack of accordance between the slant of the upland facet and the trends of the larger (pre-glacial) valleys seems to invalidate the idea of "beveling" in almost as complete a manner. We cannot doubt that one of the largest pre-glacial river-systems of Acadia lay in what are now the more or less completely drowned valleys of the Bay of Fundy and of the Cornwallis-Annapolis lowland, both of which trend at a high angle to the direction of slant of the plateau. Yet, by the hypothesis of "beveling," we should expect the northern edge of the plateau rock lying adjacent to these master-valleys to be graded to at least as flat a slope as those in the interior of the present upland, and we should look for a gradual fall of the "South Mountain" divide from Wolfville southwestwardly. We have already seen that neither of these conclusions corresponds to the facts.

Field evidence, then, seems to exclude the newest of the three hypotheses which have, up to the present time, been suggested for such a case. Whether marine or subaerial denudation must be finally appealed to for explanation of the upland facet of the Southern Plateau, cannot as yet be asserted with the confidence of full proof; to attain it, much additional field-work would be necessary. What is needed is some such evidence as that of the subaerial origin of the inland lowlands of Pennsylvania, which, on account of their enclosed nature, cannot have been effectively reached by the sea. The apparently complete lack of coastal sediments on the facet is suggestive of the subaerial explanation, but it is open to question whether such an overlap of necessarily weak rocks would not have been quite removed by general land-erosion, during the long time required to excavate the Fundy lowlands beneath the upland facet. The known inferiority of shore forces to erode as compared with atmospheric agencies of wear is not, if time enough and appropriate crustal conditions be granted, an antecedent objection to the marine hypothesis.

Yet there are certain reasons why greater satisfaction may be felt with the peneplain hypothesis. The occurrence of residuals just where the waves would have especially great destructive power can hardly be accounted for as a result of differential hardness. The very perfect adjustment of drainage-courses to soft rock-belts in the Triassic area hereafter described will be found to bear striking resemblance to similar adjustment among the trap ridges of New Jersey, and to afford grounds for a similar explanation of the phenomenon as the product of two cycles of land wasting. So close are the similarities existing between the Nova Scotian plateau, on the one hand, and the New England, New Jersey, and Southern Appalachian plateaus, on the other, that one cannot resist the conclusion that it is simplest to find a common explanation for the greater denudation in the whole belt. One of the chief recommendations for the peneplain theory as applied to the southern province is the fact that, if we grant the truth of the theory, a more complete and consistent account can be given of the multitude of land-forms associated with the larger facets. The same is believed to be true here. Bearing in mind the lack of complete demonstration for the peneplain character of the Southern Plateau, we shall yet posit such a character and proceed to inquire whether or not the topographic divisions of Acadia are in accordant, organic relationship with that facet.

EXTENSION OF THE SOUTHERN PLATEAU FACET. — In his definition of the term "peneplain" Professor Davis noted a considerable area as one of its necessary characteristics; this for the reason that, during the long lifetime of the cycle in which planation is established, denudation will hold extensive sway even over harder rocks, and they will be reduced to a lowland throughout a whole physiographic province. We expect, therefore, that if the upland facet of the Southern Plateau be of the nature of a true peneplain, it must have once extended far and wide over Acadia. It need not now be continuous, for the warping, which we believe has occurred, may be expected to have revived the old rivers of the former cycle, and to have developed new subsequent drainage in the present cycle; that, therefore, belts of lowland may be looked for wherever weak rocks appear. This deduction is realized in the facts. Where, for example, the older, harder Palæozoics appear outside of the Southern Plateau, there uplands and fragments of the peneplain are found to occur, and it is the soft Carboniferous and Triassic sediments that underlie the extensive lowlands. In fact, the various topographic divisions of Acadia from the Southern Plateau to Gaspé are perhaps best described in terms of this facet. The evidences for this statement will be more clear after a brief recital of the facts relating to each of the divisions. Since I have had the opportunity of making but one excursion and that by railway, across Cape Breton Island, and since the amount of information regarding the recent geological history of that island is scanty, I shall not attempt to speak of it in detail. From the nature of its terranes and from its geographical position, it ought to include part of the peneplain; and, indeed, from the descriptions of Campbell[1] and Fletcher (**'84**, p. 77), it would seem that the facet is excellently represented in the northern half of the island.

The Cobequid Plateau. — The Cobequid mountain belt runs nearly due east and west along a major axis about seventy-five miles long; its average and fairly constant width is from nine to ten miles. The opinion of the Canadian Survey officers has varied with respect to the age of the rocks composing these old mountains. According to the map issued by the Selwyn survey in 1886, they are pre-Cambrian, but Ells (**'97**, p. 119) has recently expressed the conclusion that they "may with propriety be regarded as more recent than the pre-Cambrian," and this is true of the granite intrusions at least, which are late Devonian or post-Devonian. In any case, however, we know that the range is composed of highly crystalline, complexly folded series of rocks that are now bounded by a rolling plateau-top from eight hundred to one thousand feet above the sea, some "peaks" reaching eleven hundred feet in altitude (Chalmers, **'95**, p. 9). The general surface of this plateau now stands at an elevation which correlates it well with the peneplain of the Southern Plateau. The extension of the latter facet would carry it over much of the Cobequids just tangent to the surface and *into* the rest of the massif, nowhere cutting it more than four hundred feet below its highest point. This close correspondence between the two plateau surfaces is explained by the assumption of one continuous peneplain as once having covered both plateaus and the intervening space. At the same time, it is possible that long low residuals of the "Unaka" type[1] overlooked the peneplain in the region of what is now the Cobequid belt.

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[1] Dawson, Acadian Geology, 2nd ed., pp. 564, 685.

THE NEW BRUNSWICK HIGHLANDS. — The lack of good topographic maps and of numerous accurately determined elevations is especially felt when the attempt is made to carry the peneplain facet into New Brunswick. Yet the grouping of facts summarized in the one-quarter inch map of the Dominion Survey with those derived from written reports seems to show that the facet is represented over considerable areas of the upland. The strongly folded Cambrian, Silurian, Devonian, and Lower Carboniferous beds wrap about the pre-Cambrian core which runs parallel to Chignecto Channel and the Bay of Fundy shore. From the eastern end of the range to a point about thirty miles northeast of St. John, all these rocks stop off at a general level of from 1,000 to 1,200 feet. The surface is gently rolling and very comparable to that of the Cobequid plateau. Still farther to the west it sinks to the 600-foot contour, where it crosses the St. John River, only to rise again to 1,200 feet and more on the northern arm of the massive angle of the New Brunswick ancient crystallines running to Chaleur Bay. Monadnocks like Bald Mt. dominate the peneplain. Below it lie entrenched longitudinal valleys presumably of subsequent origin (Bailey and Matthews, '**72**, p. 15).

NORTH MOUNTAIN, DIGBY NECK, AND LONG ISLAND. — Lastly, the upland surface of the great lava ridge that stretches with interruptions from Cape Blomidon to Briar Island, a hundred and twenty miles away, admirably represents the peneplain facet (Plates **4** and **5**). Extending the latter in imagination from the Southern Plateau to the New Brunswick highland, the nearly plane surface thus produced is found to be tangent to the summit of the intervening "mountain." From Blomidon to Digby Gut, the average elevation of the flat-topped and truncated ridge is about 550 feet, matching well with the 500-foot sky-line of South Mountain. Southwest of the Gut, the ridge-plateau breaks up into two subordinate ridges separated by a long valley. Their crest-lines accord in elevation as they sink to 120 feet on Briar

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[1] Hayes, 19th Ann. Rept. U. S. Geol. Surv., 1899, Pt. II. p. 22.

Island, while the surface of the Southern Plateau across St. Mary's Bay similarly falls toward the southwest. Apart from these noteworthy correlations, there are several arguments going to show that the trap ridge has been once peneplained. These will be best appreciated after a short account of the Fundy trough has been given.

The Bay of Fundy Trough in Geological Time. — The rocks now exposed between the Southern Plateau and the New Brunswick Highland are chiefly of Triassic (Newark) age. There is little doubt that the original extent and detailed structures of these beds cannot be determined with anything like the completeness that characterizes our knowledge of the New England Trias. It is highly probable that rocks of this age underlie the bay; but just what relation they bear to the exposed members on the shore-belts has, of course, not been made out. Even there our interpretation must be limited because of the drift-covering about the Minas Basin and in the Annapolis Valley. I have not been able to find a definite statement of what correlation can be made of possible observations or of those already published. The facts regarding the structures and history of these rocks may be noted. The scarcity of these facts will indicate the evident need of careful field-work in addition to that already done by Dawson, Bailey, and others.

The trough now occupied by the Bay of Fundy seems to have been first delimited on the south during the late Devonian, the northern rim having been defined at the beginning of the Cambrian (Bailey, **'97**, p. 107). The estuary was filled with Lower Carboniferous sediments; these were disturbed by folding in pre-Triassic times, denudation truncated the new structures, depression ensued, and thick Triassic sands and gravels were laid unconformably on the Carboniferous. Observations on the most northerly and most southerly outcrops of the Triassic show that these rocks (there chiefly of conglomeratic nature) mark old shore-zones. The consensus of opinion is that the Trias never extended much farther than the present limits of that system.

One of the youngest, if not the youngest, accessible member of the Triassic series is also one of the most important from the physiographic standpoint. I refer to the lava-flows and volcanic breccias of North Mountain and the adjacent islands including Partridge Island and the prominent Isle Haute isolated in the bay. The lowest bed is an amygdaloid conformable with the red sandstones and supposed by Dawson (**'68**, p. 93) to have been deposited beneath the sea. Above it is the massive compact trap which crowns the ridge throughout its extent. Whether or not this thick flow was overlain by sediments in

Triassic times cannot now be stated; the ten-foot layer of limestone discovered by Ells ('**95**, p. 416) on the lava near Scot's Bay is as yet an unsolved mystery.

Now the present attitude of all these beds shows that they cannot lie in their original position. From Kingsport to Blomidon and thence many miles to the southwestward, the dip is toward the north and northwest, averaging about 15°. On the opposite side of Minas Basin, it is just as characteristically to the south, as shown in the traps, sandstones, and conglomerates. This arrangement of dips and the shape of the curve terminating in Cape Split suggest a synclinal structure for this portion of the Triassic area: an imperfect "dishing" of the trap sheet after the manner of the Totoket and other ranges in Connecticut. That the same structure cannot be ascribed to the formation farther southwest is clear from Dawson's description of the occurrence at Quaco Head in New Brunswick. The soft red sandstones and conglomerates aggregate 800 feet in thickness (Matthew) and dip NNE. at angles varying from 25° to 45° (Dawson, '**68**, p. 108). Similarly the dip is north 50° near the contact with the old rocks of the Cobequid Mountains (Dawson, '**68**, p. 100). Such a persistent dip of these shore-deposits toward the crystalline highlands doubtless indicates profound faulting. It is interesting to note that Bailey and Matthew ('**72**, p. 218) early described strike-faults in the Southern New Brunswick Trias with "extensive downthrows on the south." Excepting the suspected low synclinal in the east, the Triassic beds nowhere exhibit flexures on any but the most limited scale. They have, however, been so disturbed as to show typical monoclinal structure. No important duplication of strata has yet been proved, but there are indications that the general NW dip is due to block-faulting suggestively like that in the Connecticut Valley. In the long section of the "sea-wall" at the head of St. Mary's Bay, Bailey ('**98**, p. 124) describes many small faults with the upthrow constantly on the north. Bailey ('**98**, pp. 126, 127; '**98**, p. 358; '**97**, p. 114) further notes other faults at Digby and at Granville, and also states his general conclusion that the trough has been "faulted" in the direction of the axis of the bay. It is further possible that one or more faults may explain Bailey's ('**98**, p. 357; '**98**, p. 126) discovery of trap conglomerate lying adjacent to the lava ridge of North Mt., the conglomerate having been a contemporaneous deposit since faulted down to its present position.

The constructional topography resulting from these movements must have been very different from that of the present time. The sandstones of the lowland belts probably extended along their planes of stratification to altitudes higher than the existing summit-line of North Mountain. The traps must certainly have stretched upward for some distance beyond the same line. One evidence for this is found in the independence of the longitudinal ridge-profile and the dip of the trap; at Blomidon it measures 15°, at Digby Gut, 5° to 10°; near Bridgetown the beds lie horizontal (Bailey, **'98**, p. 128). Yet we have seen that the upland level remains very constant at about 550 feet throughout the whole distance including these three points. The truncation of the constructional ridge is even more clearly shown in the transverse profiles. A good example appears in the extended view which one gets toward the southwest from "Look-off," near Canning (Plate **8**). There the upland surface is flat and nearly level, without a decided slope to the north until the Fundy sea-cliff is reached, while the dip is about 15° to the north. It is the perfect level-topped sky-line of a typical plateau, not that of the back-slope of a tilted lava-block. Such a sky-line would be extremely difficult to explain as belonging simply to the retreating escarpment of a trap sheet, wasting during the first cycle following uplift. Nor could the doctrine of "beveling" be applied here with any success; more probable would be the hypothesis of marine erosion.

The key to the problem is to be found in the sympathetic relationship already described between the upland facet of the Southern Plateau and this other one of North Mountain. The latter is a residual of the grand peneplain which we have traced from Cape Sable to the Cobequids, the New Brunswick Highlands, and beyond. The peneplain was tilted, its streams invigorated, and thereby narrow valleys were cut in the harder pre-Carboniferous rocks, and the lowland from Truro to the mouth of St. Mary's Bay on the soft Triassic sandstones. In order to understand this and the adjoining lowlands of Acadia, it will be well to determine as nearly as may be, and more in detail than heretofore, the amount and directions of tilting which the peneplain has suffered, and thus get some idea of the constructional relief at the beginning of the second cycle. In thus treating of the deformations of a baselevelled land-surface, it is realized that we are taking another step in the direction of pure theory; but, if the peneplain explanation be regarded as correct, the step is necessary.

WARPING OF THE UPLAND PENEPLAIN. — As suggested on an earlier page, the most significant displacement of the peneplain from its original position near sea-level consisted in a tilt directed about S. 30° E., affecting nearly uniformly all parts of the facet east of a line passing through St. John and Digby. This differential movement must have been greater than is now registered in actual elevations. Recent studies have shown that the whole coast of Acadia has been lately drowned to a fairly uniform depth of about 250 feet. Adding this figure to present heights, we find that the peneplain must have once stood above sea-level 1,250 to 1,450 feet in Southern New Brunswick, 1,050 to 1,250 in the zone of the Cobequids, 800 feet along the axis of North Mountain, and at sea-level some score of miles to seaward of the existing southeast Atlantic coast-line. The maximum uplift occurred in the New Brunswick Highland, for there is reason to believe that the facet was on the northwest warped down toward the great Carboniferous basin. This may have been in the nature of a revival of crustal energies acting along the same axis of warp which located the original Devonian basin, and parallel to which post-Pleistocene faulting has taken place (Matthew, '**94**, pp. 35, 36).

A secondary warp, transverse to the first one mentioned, seems to have affected the facet west of the St. John-Digby line, produced to Cape Sable. The relatively rapid fall in the crest-elevation of the Triassic trap ridge from Digby Gut to Briar Island certainly suggests a direction of tilt different from that of the eastern division of the ridge. Corresponding thereto is the similar westward slant of the facet from a point twenty miles east of the St. John River, and on the Southern Plateau west of Digby. Finally, this westward tilt would explain the low position of the ancient peneplained rock-surface at Passamaquoddy Bay and in the State of Maine.

The Second Cycle: the Development of the Triassic Lowlands.

One immediate result of these warps would be the revival of the rivers that lay on the peneplain. This would mean the wearing out of valleys beneath the facet, especially on the less resistant rocks. On account of stream adjustment inherited from the long preceding cycle, the soft belts would at the initial stage of the new cycle, be subject to particularly rapid attack. Since those belts are longitudinally arranged, their respective valleys and valley-lowlands would have Appalachian trends. Such, in brief, is believed to be the origin, not only of the Cornwallis-Annapolis Valley (Plate **6**), but also of the valleys now drowned to form the Minas Basin (Plate **10**), Chignecto Channel, St. Mary's Bay, and possibly the Bay of Fundy itself. It is evident that we cannot decide these questions of origin with all desired fulness, for stream erosion has here been strikingly supplemented by marine and glacial erosion, and the effects of all further complicated by possible down-warping along the axis of the Bay of Fundy.

Of the four factors, glacial erosion may be safely excluded from the list of important causes on account of its insufficient amount. On the other hand, some sort of denudation has taken place. In the field it is clear that the edges of the upturned sandstones and conglomerates in all these embayed areas are truncated, and in such a way as to suggest excavation of once filled troughs rather than a down-warping of the general peneplain.

There can be no doubt that abrasion of the Fundy shores by wind waves is enormously aided by tidal scour; in the Annapolis Valley at least, the wind wave could never have rivalled the tidal as an erosive agent. It is but natural to inquire as to the value of such tidal action in explaining the lowlands round about. If the present rate of retreat of the cliffs on the western shore of the Minas Basin were maintained, it is very possible, if not probable, that the sandstones of the Annapolis Valley as far as the source of the Cornwallis River would be reduced to a surface below the level of low tide before atmospheric erosion could produce an ultimate plain of denudation over the same area (Plate **5**). We know as a matter of fact that the basin has been considerably enlarged in Quaternary time. May we believe that the tidal currents working here, in the Annapolis Basin, in St. Mary's Bay, in Chignecto Channel, and in Northumberland Strait, would, at the completion of the "tide cycle" already begun, succeed in producing a submarine plain of erosion comparable to the once continuous floor of the Annapolis, Colchester, and Cumberland lowlands? Might this be done before any serious damage had been caused to the present form of the harder rocks of the Southern Plateau? At present, we can see no reason why these questions should be answered in the negative. Hence, we must conclude that, if the conditions of the time of excavation were like those of the present, these lowlands, although in part the result of subaerial erosion, might have been to the greater extent produced by tidal scour operative at first in a number of *rias*, and then, at the close of the tide cycle, in a long sound stretching from what is now the Bay of Fundy to Northumberland Strait.

But it must be remembered that, if our theory of the upland facet be correct, the constructional shore-line at the beginning of the second cycle was far removed from the existing one. St. Mary's Bay did not exist then. The Bay of Fundy extended no farther to the east than what is now Digby Gut, and it was narrower than now. The amount of work to be done in excavating a submarine platform of erosion in the sandstones was thus vastly greater, both as to thickness and area, than the amount required to complete the present "tide cycle." Moreover, the tidal currents would be much less powerful than now, both at the beginning and end of the longer cycle; they would probably be similar to the tides of the Maine shore in the first stage and not much higher in the last. Chalmers (**'98**, p. 19) has calculated that, if the Chignecto Isthmus were submerged, the tides would not average more than 10 or 15 feet in range, giving a ratio of scour for the corresponding currents not much greater than in Massachusetts Bay. Yet the isthmus must have been submerged if the Triassic and Carboniferous lowlands were in reality due chiefly to tidal scour. Destroying the conditions of the present unusual tides, more normal flood and ebb currents would be called on to do work on a scale that has not been paralleled elsewhere.

Such submergence obtained during the Saxicava Sand period. The Fundy region was then depressed "at least" 120 feet according to Chalmers (**'95**, p. 18), 220 to 225 feet according to Dana.[1] Corresponding to our deduction, the "Champlain" sea-floor, revealed in the existing deposits at Middleton, shows evidence of relative quiet. Their wide extent seems to indicate that tidal scour was then powerless to remove unconsolidated material from the floor of the Annapolis Valley, much less excavate the Triassic sandstones. Even more striking is the occurrence of similar sands in Sandy Cove and on the slopes of the Petit Passage, in each of which there is a heavy tidal rip. Ebb and flood currents must have been weak in those days. But, weak as they were, the conditions were certainly more favorable to scour than they would have been if there had been no open funnel-like Bay of Fundy to furnish concentration.

Now, in addition to the fact that we do not know how much ability for excavation on the part of the tides is at our disposal during the time elapsing after the warping of the peneplain, we have the second great difficulty that we do not know the exact form of the Bay of Fundy when the warping was finished. We might imagine that during the long period of the previous cycle, tidal currents had conspired with atmospheric erosion to open a channel from the Bay to the Gulf of St. Lawrence. The same result would be reached if the old subsequent valley were slightly deepened by crustal warping. In either case, with the slow uplift of the land, these currents might excavate the channel fast enough to keep pace with the elevatory process, thus affording an example of an

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[1] Manual of Geology, ed. 4, p. 984.

"antecedent" tidal run-way or sound of great dimensions. Or it might be that the tilting of the peneplain was so rapid as nearly to obliterate the Bay of Fundy of that time. Could the weak tidal currents then deepen and lengthen the remnant of the bay as well as remove the large amount of land-waste brought to the shore by the revived streams? Again, would the minor oscillations of level expected during the long period following the last great uplift, occasion repeated drowning of the river-valleys and therewith increased excavating power of the currents, a power perhaps comparable to that of the present Fundy tides? Similar questions would arise in the discussion of the ideal "tide-cycle," which is yet to be invented. Where so little has been done towards discovering the criteria for a tidal plain of denudation as distinguished, from a peneplain or from platform of wave-erosion, it does not seem possible to get very far in finding a complete history of the Bay of Fundy. There are too many unknown elements in the problem to permit of its complete solution. We are sure that tidal work cannot be ruled out; we know as well that certain facts lead to the conclusion that a part, perhaps the major part, of the excavation has been done by subaerial processes.

Some of these facts have been already noted. In addition, it may be questioned that the gates opening into the Annapolis-Cornwallis Valley, are wide enough to permit of the entry of efficient tidal currents to any considerable distance from the gates, even under the present conditions of extraordinary tidal ranges. These openings are wider now than they have ever been before; yet scouring action is confined to the vicinity of St. Mary's Bay, Digby Gut, and Minas Channel, and elsewhere deposition is taking place. Secondly, the development of the Trias at the sea-wall, at Bridgetown, at Middleton, and at other points in the valley seems to show a greater sympathy of the pre-glacial bed-rock topography with pre-glacial St. Mary's, Annapolis, and Cornwallis *rivers* rather than with the graded slopes towards St. Mary's Bay and Minas Channel expected if the tides did the excavation. At least one other large feature of the unsubmerged Triassic suggests river-work, and it is fair to lay emphasis on even a single instance of the kind where so much of the physiographic record is drowned beneath the waters of the bay. I refer to the long trench which has been hewn out of the amygdaloid lying between the two trap ridges of Digby Neck. Here, as in the case of the Annapolis Valley, tidal erosion would be very unlikely to produce a submarine valley of such length and narrowness. The six-knot flood and ebb past the southwest ends of Long and Briar Islands does not seem to be appreciably lengthening, by differential erosion, the small inlets located on the amygdaloid. The trench has, on the other hand, all the appearance of a subsequent valley worn out in the second cycle by a river already well adjusted in an earlier cycle. Finally, we shall see that the structure and topography of the Acadian Carboniferous areas will suggest a subaerial origin for the neighboring Triassic lowland. The broad, low, gently rolling plains of the Colchester and Cumberland districts flank the Cobequids, and are continuous with the great Carboniferous lowland of New Brunswick on the northwest. Their discussion will be postponed until the date of the upland facet has been fixed, for this date will be found to have an important bearing on the problem of their interpretation.

Granting a subaerial origin for the Triassic lowland, it is natural to attempt a scheme for the pre-glacial drainage that conditioned the erosion. It is evident that the picture must be incomplete. Much of the drainage must have been longitudinal. Some of it was transverse through courses still well preserved in the notches at Digby Gut, Sandy Cove, Petit Passage, and Grand Passage (Plate **7**). At least two of these are located on faults causing dislocations in the trap visible in the field.[1] The offsetting of the trap ridge at all four notches is most simply explained by as many upthrows on the west. It looks as if these faults were older than the upland peneplain, that either a consequent stream of the former cycle or a later subsequent stream occupied each fault-zone, and that the notch in each case was deepened about as fast as the adjoining lowlands were worn out. In like manner, the Connecticut traversing the Holyoke range in Massachusetts has kept open its notch, the product of two cycles. Since the recent drowning of southwest Nova Scotia, tidal scour has somewhat widened the passes. In passing, it may be noted that the fault at Digby Gut lies close to the hinge-line about which I have posited the westward warping of the peneplain.

THE GEOLOGICAL DATES OF THE PENEPLAINS. — In the absence of the sediments which must have been deposited on the sea-floor during the formation of the peneplain, it is not possible to deduce directly the date of the facet in geological time. If I am right in correlating the upland facets of North Mountain and the Southern Plateau, it follows that the peneplanation must have occurred in post Triassic times. Beyond this general fact, the Acadian record will not permit us to go, except as that record is interpreted in terms of better known regions. Using the latter principle, the completion of the Nova Scotian peneplain may be provisionally referred to the close of the Cretaceous period. The grounds for this reference will be readily appreciated by those conversant with the similar land-forms of the southern Appalachians, where the dating of the plains of denudation does not admit of essential doubt. The general resemblance as to hardness among the rocks of North Carolina, Pennsylvania, New Jersey, and Nova Scotia, the striking similarity in Jurassic constructional topography in the four regions, and the equal completeness of the planation, lead us to infer in Nova Scotia, as in the other regions, that the peneplain was finished only after a large part of post-Triassic time had elapsed. Again, from the study of sediments in the southern Appalachian, it has been determined that the disturbance of each peneplained area from its position near base-level must have occurred in late Cretaceous or early Tertiary time. Most of the destruction wrought on the peneplains by subaerial erosion has been carried out during a Tertiary cycle that was not ideally completed. The opinion of those best qualified to speak on the subject is, then, that these classic regions of the south have been wasting through post-Triassic time. This long period has been almost wholly occupied in the doing of two pieces of work, — the development of a Cretaceous peneplain covering each region entirely save for local monadnocks, followed by the etching out of Tertiary lowlands on the soft rocks and narrow Tertiary valleys on the hard. In Acadia, we have a parallel series of events. At present, I can discover no more trustworthy guide for the dating of upland and lowland facets than in this strong analogy. As is well known, the recognition of two cycles in New England and their placing in the geological record have been influenced by similar evidence and a like analogy. It is of course evident that in Acadia we are far from our physiographic base of supplies; and the relations of these distant fields can bespeak no more than a strong probability for the conclusions stated.

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[1] Dawson, Acadian Geology, ed. 2, p. 96. *Cf.* Bailey, Geol. Surv. Canada, Ann. Rep. M., 1896, Vol. 9, p. 131, and Dawson, *op. cit.*, p. 95.

THE CARBONIFEROUS LOWLANDS. — The Carboniferous of Cumberland County has been described in great detail by Logan and Dawson (Acadian Geology, ed. 2, p. 150), and we have added information in the Canadian Survey Report for 1895. The long section on the shore of Chignecto Bay, including the famous cliffs at South Joggins, has furnished the key to the whole area as well as to the structures of the Carboniferous elsewhere in Acadia. These beds aggregate nearly fifteen thousand feet in thickness and represent all the larger subdivisions of the whole Carboniferous system. In Permian time, they were strongly folded with a general synclinal arrangement along an axis running roughly parallel to the Cobequid belt, the dips at South Joggins averaging 19° and in other parts from 0° to 45° or more (Plate **9**). Strata characterized by such thickness and so diverse attitudes must have been covered by a constructional topography of relatively great strength. That topography is now lost, and a new one has taken its place. From the railroad station at Wentworth, one looks down over a vast expanse of this Carboniferous district and is struck by its evenness (Plate **9**). A vast plain lies before the observer. It is highest at the three hundred-foot contour where it abuts against the Cobequids. Farther away, it sinks to an average elevation of two hundred feet, which persists throughout most of the basin, except where narrow valleys are incised below the plain. The plain is not absolutely level, but is gently rolling, as is typically displayed on the railroad from Maccan to South Joggins and along the Joggins shore.

The rocks of the Colchester district differ from those of Cumberland in including only the Lower Carboniferous series and therewith a larger proportion of limestones than occur in the northern trough. The structures are here more complicated. The beds stand at all angles to the horizontal plane and are frequently interrupted by faults of large throw. The great gorge at Truro affords an especially fine view of the steeply inclined sediments. The present topography is again, however, quite independent of structure. The lowland stands at an average height above the sea of about two hundred feet. Gentle ridge-like swells on the harder beds break the monotony of an otherwise nearly perfect plain, in which youngish valleys are sunk, comparable to those of Cumberland County.

Now, in accounting for this great amount of denudation in both districts, we have not only to deal with a possible Jura-Cretaceous cycle and a possible Tertiary cycle; some place must be made for the enormous Permian denudation implied by the unconformity between the Carboniferous and the Triassic, and for Triassic denudation on unsubmerged Carboniferous. Then, too, a mid-Carboniferous period of subaerial conditions must have elapsed, since we find an unconformable relationship between the Lower and Middle Carboniferous strata. However, notwithstanding this latitude offered us in placing the dates of the various erosion-periods which, from time to time, have worn down the constructional Carboniferous relief, I have come to the belief that the existing lowlands owe their existence essentially to the same Tertiary cycle of wasting that explains for us the Annapolis Valley.

If the lowland were existent in pre-Cretaceous time, it must have been submerged to greater or less depth during the Cretaceous cycle, and sediments of that age must have been laid in the trough. While most of such a filling might have been removed during the Tertiary cycle, we should hardly expect that every trace of it would have vanished. Nor is it conceivable that the present surface of the lowlands represents down-warped or down-faulted portions of the Cretaceous peneplain. Neither faults nor warps would so faithfully occur only where the soft Carboniferous rocks appear; yet in this part of Acadia the Carboniferous rocks and the lowlands are coextensive. No fact regarding the lithology of these sediments is more strikingly brought home to the field-observer than their similarity to those of Triassic age in the Fundy trough, — a similarity which goes far to explain the long delay in transferring the red sandstones of Prince Edward Island from the Triassic to the Carboniferous division, where recent determinations would place them. The rocks of both periods are about equally consolidated and equally resistant to atmospheric wasting. If the Annapolis Valley be the product of erosion in the Tertiary cycle, we must agree to the *possibility* of similarly profound dissection of the Cretaceous peneplain in the Carboniferous tracts.

For these reasons, and on account of the agreement of summit-levels on Triassic and Carboniferous rocks at the head of the Bay of Fundy, it is highly probable that the lowland surface from St. Mary's Bay to Northumberland Strait belongs to one great plain of denudation dating from the end of the Tertiary cycle. This plain is a secondary peneplain, and is believed to extend over Prince Edward Island and the Carboniferous lowland of Central New Brunswick. Its longitudinal valleys described by Sir William Dawson are regarded as the product of adjustment. Surmounting the plain are monadnocks like Springhill (610 feet), Claremont Hill (565 feet), Windham Hill (600 feet) in the Cumberland district, Indian Mountain north of Moncton, and the 500-foot hills in the interior of Prince Edward Island. The Cobequid Plateau is of the nature of a "catoctin." The steep-walled gorges through the plateau at Wentworth and at Halfway River are conceivably of the nature of "shut-ins," and due to the erosive work of transverse streams let down from the levels of the Cretaceous peneplain. The latter notch was lowered as fast as the soft Carboniferous rocks were removed in the lowlands by a stream persistent in its course until glacial times. The rock-basin of Folly Lake seems to show that the Wentworth notch early became a wind-gap during the Tertiary cycle. Chalmers (**'95**, p. 13) suggested an antecedent origin for the Halfway River Pass, but he has not brought that hypothesis into relation with a coherent scheme of physiographic development for the whole region.

Dissection of the Tertiary Peneplain; Drowning and More Recent History of Acadia.

This peneplain of the second cycle was uplifted probably with differential movement during the later Tertiary. A new, third cycle was thus introduced, and numerous valleys were sunk to considerable depths beneath its surface. This cycle has been interrupted several times by changes of level, the most significant of which was the positive movement of sea-level whereby the lower courses of many of the rivers have been drowned. In this way, the valleys of the Miramichi, Richibucto, Buctouche, Shubenacadie, Avon, and other rivers have been turned into tidal estuaries. The trends of the valleys opening into the eastern end of the Bay of Fundy seem to show that these valleys belong to one great river-system. This has since been drowned probably by the same wholesale down-sinking that explains the estuaries of eastern New Brunswick, and of the Nova Scotian seaboard. In the light of present knowledge, it cannot be definitely stated whether Northumberland Strait represents part of a drowned river-valley or the locus of a northwest-southeast trough due to crustal warping. Just how far such warping has affected the Tertiary peneplain cannot be made out without better topographic data, better maps, than we now have at command.

The general depression of Acadia developing the estuaries was followed by an elevation of varying amount in different areas. The post-glacial marine plain of Middleton dates from this last uplift. Much more extended coastal plains of the same age fringe Chaleur Bay, the whole eastern coast of New Brunswick, and the coast of Maine.

Still more modern are the famous tidal flats of the Fundy trough, the sand-beaches and bars and the dune-belts of the coast, the fine palisade-like cliffs which the waves, aided powerfully by tidal scour, are driving inland, and the resulting marine benches of Minas Basin, Chignecto Channel (Plate 8), and of the Bay of Fundy proper. Excavation by tidal scour is now going on apace at Minas Channel, at Digby Gut, and at the passes on the southwest, where all these gates are every day opening wider.

Summary.

The attempt has been made in the foregoing sketch to show, first, that Acadian land-forms may be described in terms of two topographic facets, each a nearly perfect plain of denudation, interrupted by incised valleys and surmounted by residual hills; secondly, that there is evidence to show that the denudation was essentially subaerial and referable to two chief cycles of geographic development. This evidence, though not so complete, is of the same quality as that used in the best extant treatments of similar facets in more southerly portions of the Appalachian system. Finally, the following table will summarize the very striking parallel which can be drawn between the physiographic features of Acadia and New England. The similarity between the two provinces is here expressed in terms of a theory of development, but the homologies between the greater facets and the details of relief exist independently of theory. Extending the comparison to the central and southern Appalachians would from this standpoint of physiographic history still further establish the organic unity of the whole system from Georgia to the Gulf of St. Lawrence.

HOMOLOGIES OF LAND-FORM AND OF THE DETERMINING STRUCTURES IN ACADIA AND NEW ENGLAND.

ACADIA.	NEW ENGLAND.
The Cretaceous Peneplain:	*The Cretaceous Peneplain:*
Represented by the upland facets of	Represented by the upland facets of
a. The Southern Plateau, corresponding to	*a.* The Eastern Plateau of New England.
b. The Southern New Brunswick Highlands, corresponding to	*b.* The Berkshire Plateau, and Western Plateau of Connecticut.
Characterized by:	Characterized by:
a. Location on folded Palæozoic rocks of Appalachian trend	*a.* Location on folded Palæozoic rocks of Appalachian trend.
b. Monadnocks	*b.* Monadnocks.
Deformed by broad arching along an axis of Appalachian trend and by a westward tilt of the peneplained area lying west of the meridian of St. John, N. B.; accordingly the Southern Plateau has a seaward slant corresponding to	Deformed by a general southeastward tilt accordant with an axis of warping of Appalachian trend; there results the seaward slant of the Eastern Plateau of New England.
Modified by:	Modified as the Cretaceous peneplain of Acadia:
a. The incision of transverse and longitudinal valleys	*a.*
b. The drowning of the shore-line	*b.*
c. The removal of residual soils by glaciation	*c.*
d. The remodelling in detail of pre-glacial topography by glacial erosion	*d.*
e. The extensive obliteration of pre-glacial drainage on the plateaus by an irregular veneer of glacial débris; as a result superposed drainage	*e.*
The Tertiary Peneplain:	*The Tertiary Peneplain:*
Represented by:	Represented by:
a. The lowlands about the Bay of Fundy, corresponding to	*a.* The Connecticut Valley Lowland.
b. The Cumberland, Colchester, and Central New Brunswick lowlands, corresponding to	*b.* The Lowland of the Narragansett Basin.
Characterized by:	Characterized by:
a. Location on:	*a.* Location on:
(1) Triassic sandstones with monoclinal structure, of Appalachian trend	(1) Triassic sandstones with monoclinal structure, of Appalachian trend.
(2) Folded Carboniferous sediments	(2) Folded Carboniferous sediments.
b. "Catoctins," residuals of tilted trap-sheets of Appalachian trend; *e. g.* North Mountain	*b.* "Catoctins," residuals of tilted trap-sheets of Appalachian trend; *e. g.* the Eastern Trap Range of Connecticut, including Higby Mountain, etc.
Transverse notches in the catoctins, located on cross-faults; *e. g.* Digby Gut, Petit Passage	Transverse notches in the catoctins, located on cross-faults: Vineyard Gap, Reservoir Gap in the Hanging Hills, Connecticut.
Modified by:	Modified by:
a. The excavation of narrow valleys at the beginning of a third cycle; trenches in the Carboniferous Lowlands	*a.* The excavation of narrow valleys at the beginning of a third cycle; trenches in the Narragansett Lowland.
b. Subsequent drowning of these valleys and of a large part of the lowlands to form the Bay of Fundy and the adjacent Basins	*b.* Subsequent drowning of the lower Connecticut River Valley to form New Haven Harbor; formation of Narragansett Bay.
c. Local veneers of marine Quaternary sands exposed by recent partial emergence	*c.* Widespread veneer of terraced Quaternary sands.
d. Considerable destruction of the lowland terranes by tidal scour.	

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EXPLANATION OF PLATES.

PLATE 1.

View of the lake-covered Southern Plateau at Maitland, eighteen miles south of Annapolis, Nova Scotia.

PLATE 2.

View of "South Mountain," the northern edge of the Southern Plateau, at Digby, Nova Scotia; the Annapolis Basin in the middle ground.

PLATE 3.

Gaspereau Village and Valley of the Gaspereau River, which lies intrenched in the even-topped Southern Plateau. Looking south.

PLATE 4.

North Mountain, seen across the drowned Tertiary lowland, from Wolfville, N. S.

PLATE 5.

View of North Mountain at Cape Blomidon, showing the flat sky-line. In the middle ground is seen the Tertiary peneplain level and the sea-cliff in tilted Triassic sandstone.

PLATE 6.

The Triassic lowland seen from "The Look-off," near Canning, N. S. The even sky-line of the Southern Plateau in the background. Compare the view of the Connecticut Valley Lowland published in the 18th Ann. Rept., U. S. Geol. Surv., Part II., Plate 1.

PLATE 7.

Digby Gut, looking south toward Annapolis Basin.

PLATE 8.

View of North Mountain, looking west from "The Look-off," near Canning, N. S.

Sea-bench at South Joggins, N. S., seen at half-tide, looking west.

PLATE 9.

View of the Cumberland lowland from Wentworth Station on the Cobequid Plateau. Looking northeast.

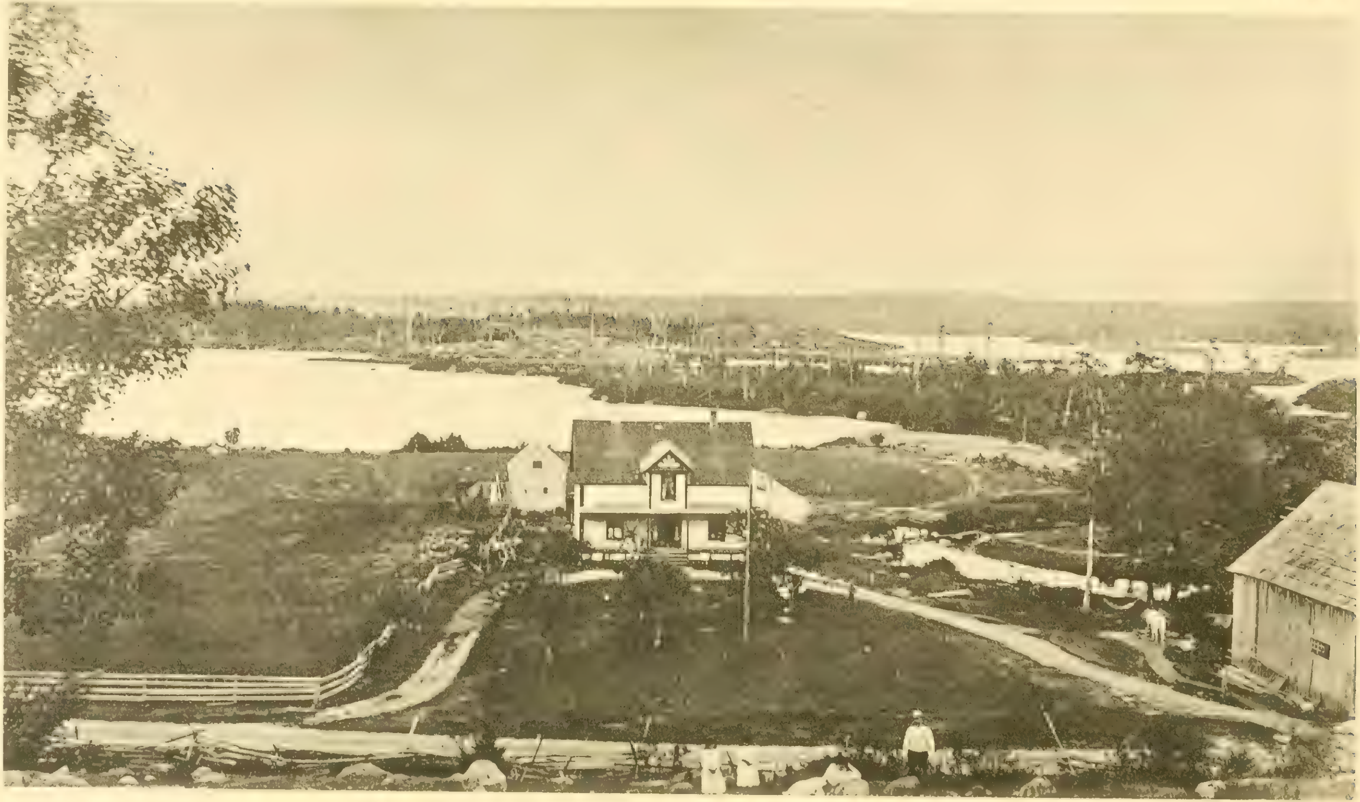
Tilted Carboniferous sandstones and shales overlain by drift at South Joggins, N. S. Looking east.

PLATE 10.

Minas Basin and the Triassic lowland, seen from North Mountain, near Canning, N. S.

PLATE 11.

Map showing the occurrence of Cretaceous and Tertiary peneplains in Acadia.



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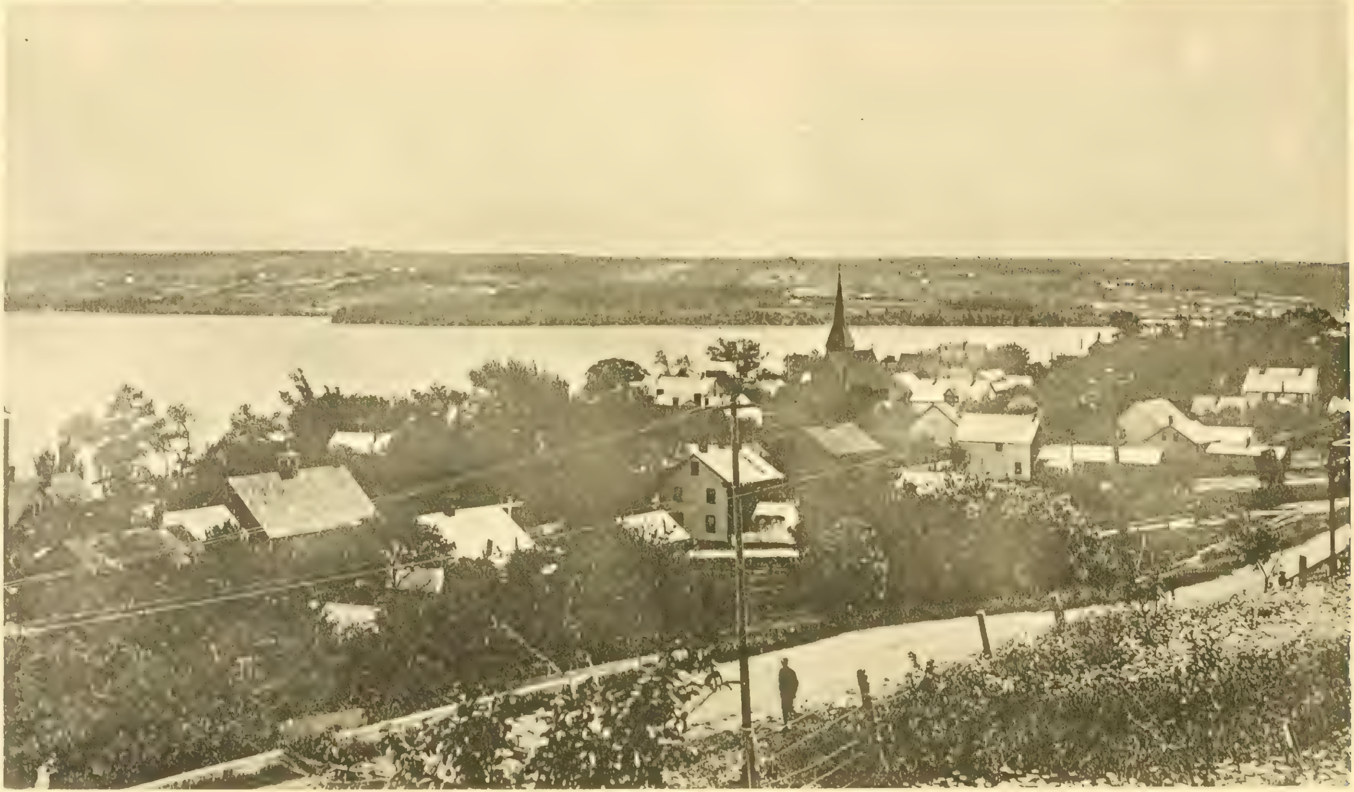
THE SOUTHERN PLATEAU AT MAITLAND, N. S.



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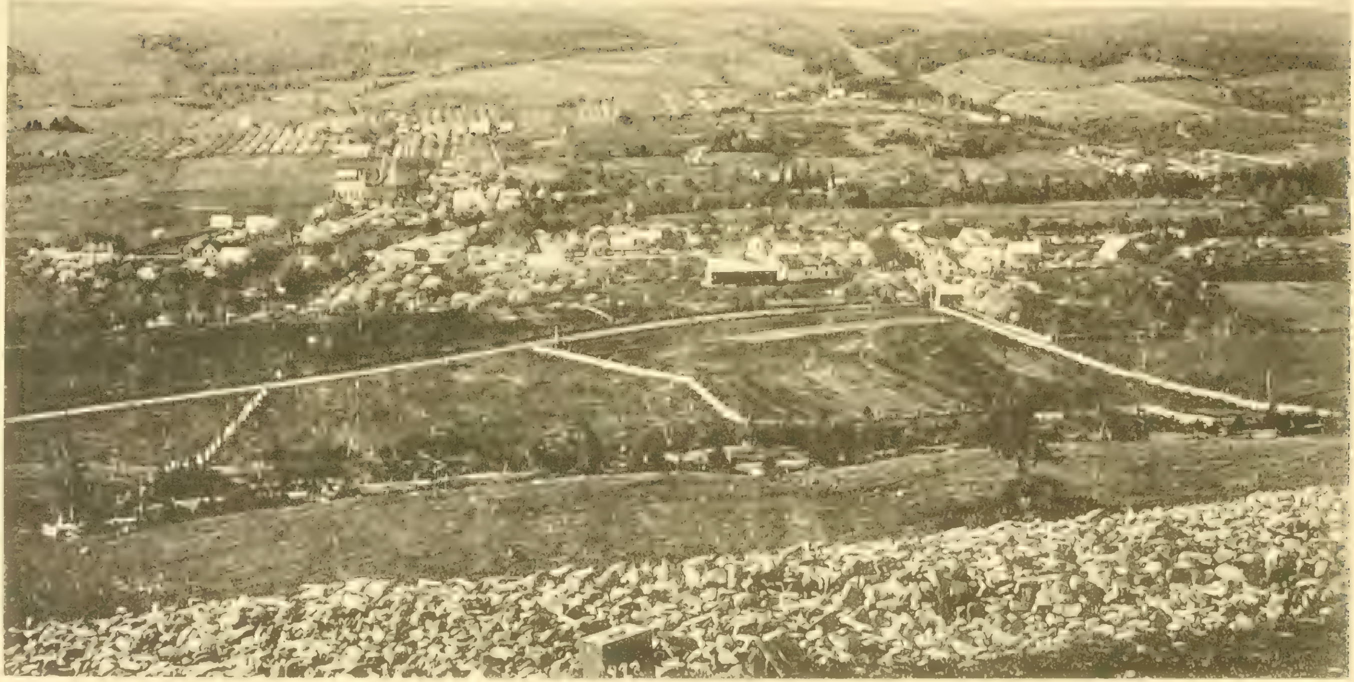
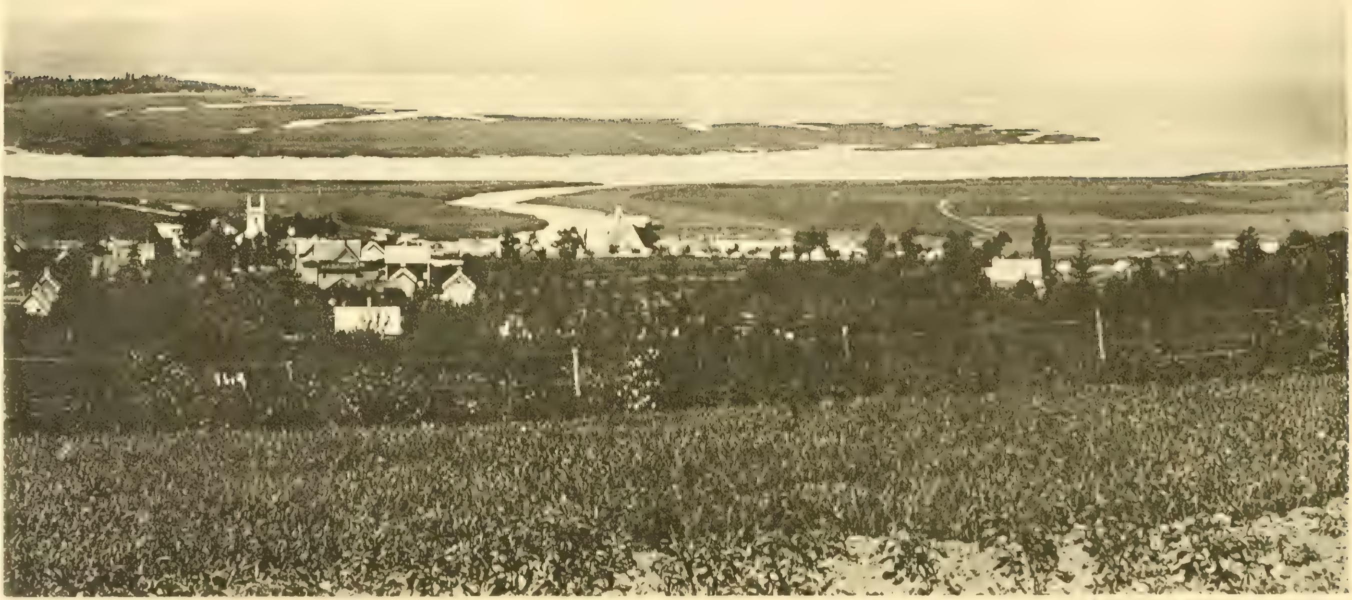
"SOUTH MOUNTAIN" AT DIGBY, N. S



GASPEREAU VALLEY, N. S.



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NORTH MOUNTAIN, FROM WOLFVILLE, N. S.

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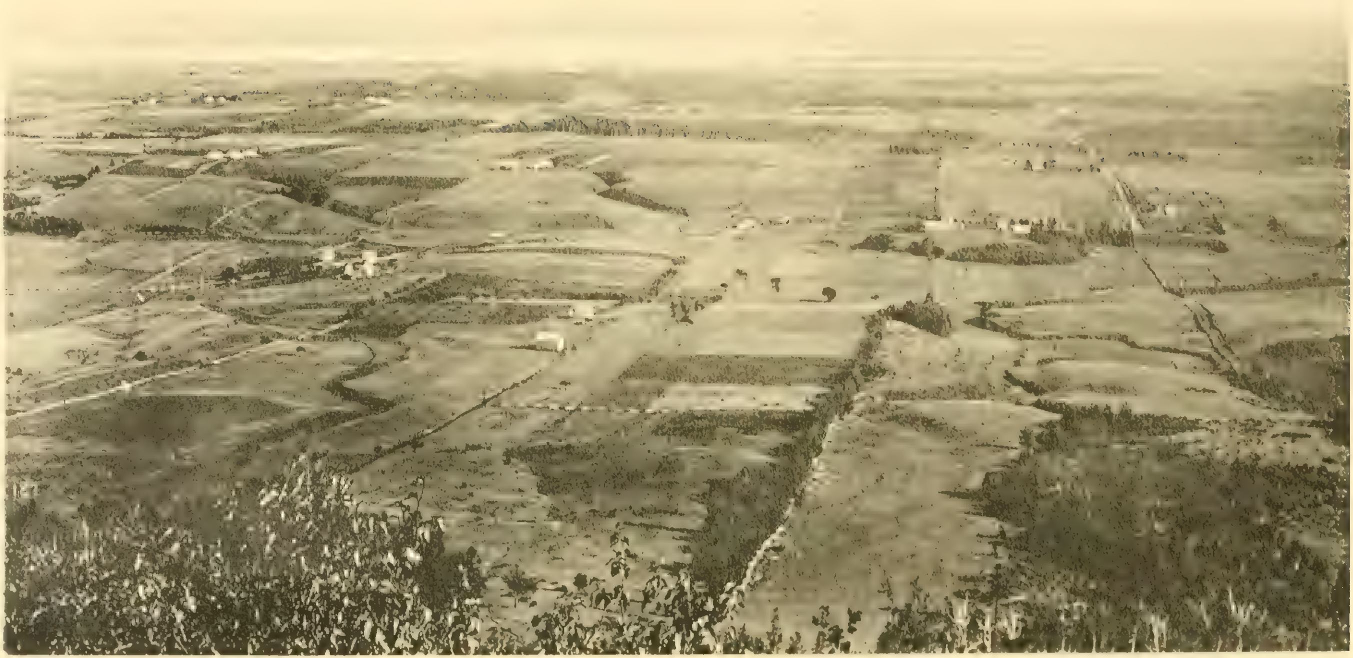
CAPE BLOMIDON.



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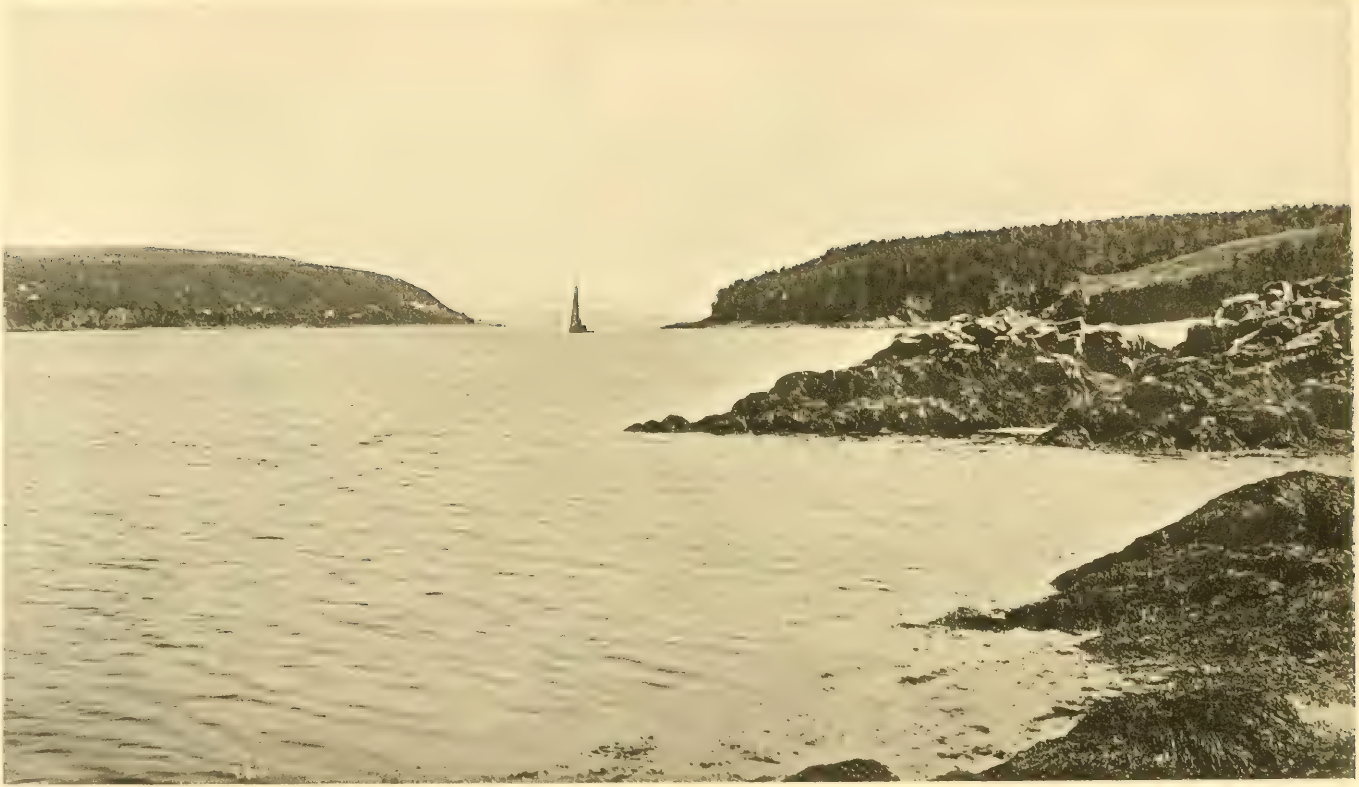
TRIASSIC LOWLAND NEAR CANNING, N. S.



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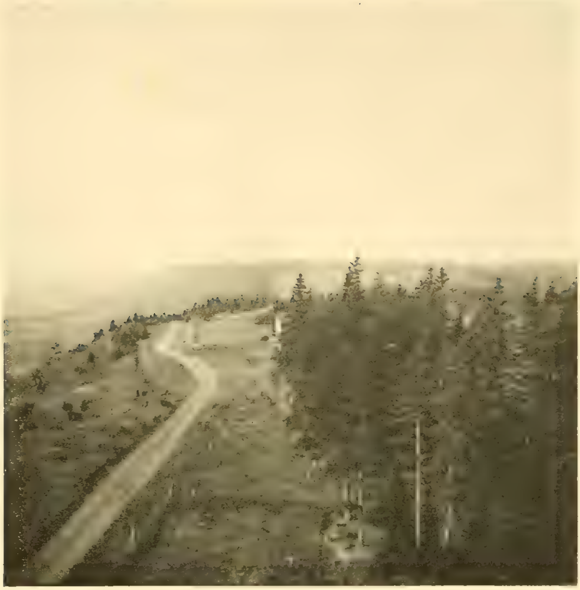
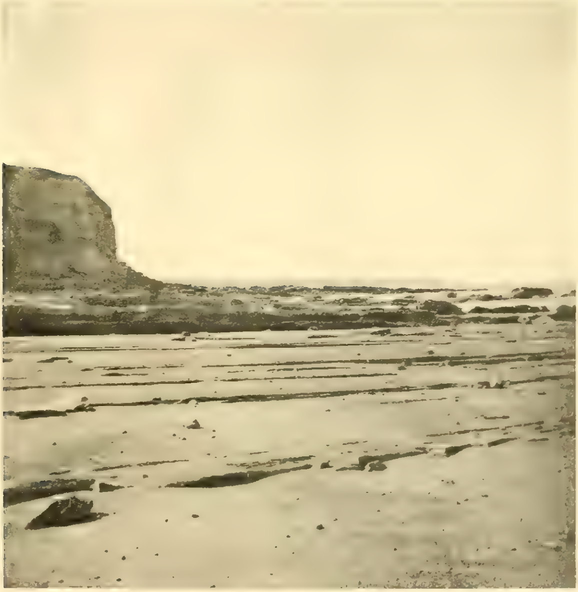


NORTH MOUNTAIN FROM "LOOK-OFF."



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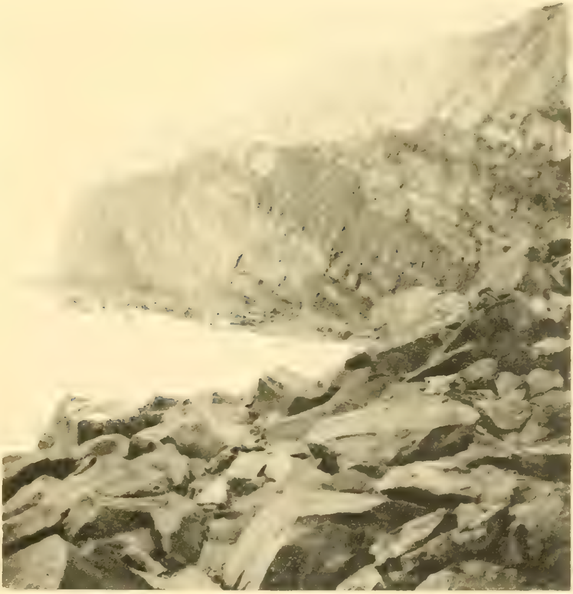
CUMBERLAND LOWLAND.



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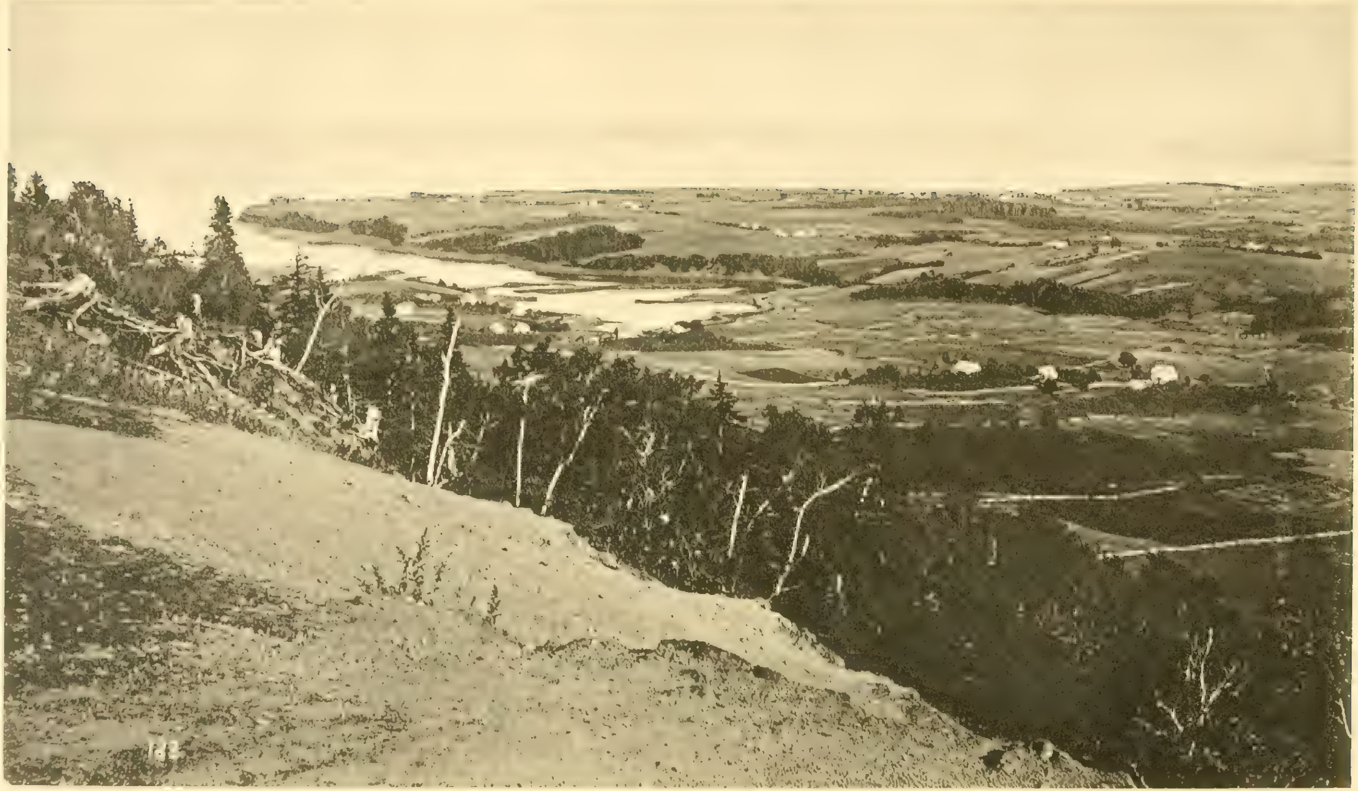
STRUCTURE AT SOUTH JOGGINS, N. S.



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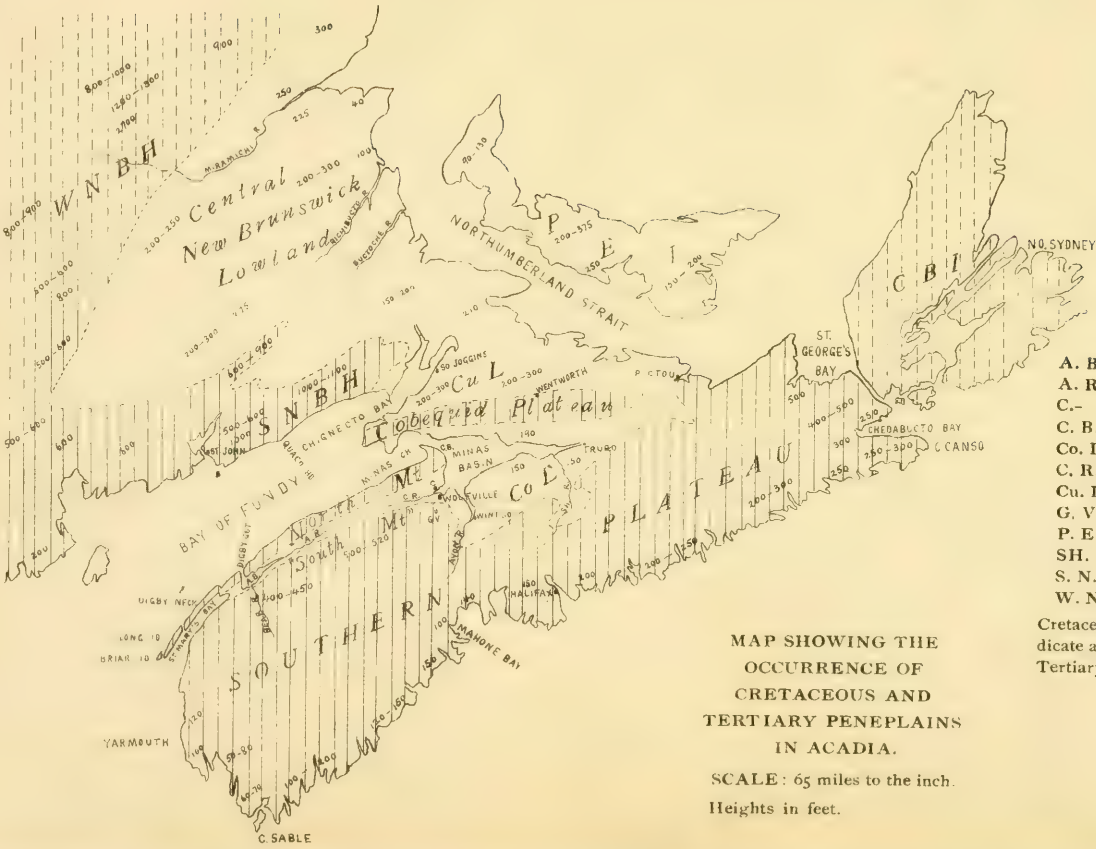
MINAS BASIN AND TRIASSIC LOWLAND.


W N B H
Central New Brunswick Lowland
S N B H
Cu L
Cobequid Plateau
P E I
C B I
North Mt
South Mt
Co L
SOUTHERN PLATEAU
NORTHUMBERLAND STRAIT
BAY OF FUNDY
CHIGNECTO BAY
MINAS BASIN
MINAS CH
ST. GEORGE'S BAY
CHEDABUCTO BAY
C CANSO
NO. SYDNEY
P CTOU
WENTWORTH
TRURO
JOGGINS
ST JOHN
QUACO
WOLFVILLE
WINDSOR
HALIFAX
MAHONE BAY
DIGBY GUT
DIGBY NECK
ST. MARY'S BAY
LONG ID
BRIAR ID
YARMOUTH
C. SABLE
MIRAMICHI R
RICHIBUCTO R
BUCTOUCHE R
AVON R
BEAR R
A.B.
C.R.
G.V.
C.
SH. R.
300
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1200-1800
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600-900
1000-1100
500-600
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200-300
90-130
200-375
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250
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120-150
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100
100
400-450
500
520

MAP SHOWING THE
OCCURRENCE OF
CRETACEOUS AND
TERTIARY PENEPLAINS
IN ACADIA.

SCALE : 65 miles to the inch.

Heights in feet.

EXPLANATORY.

A. B.-	Annapolis Basin.
A. R.-	Annapolis River.
C.-	Canning.
C. B. I.-	Cape Breton Island.
Co. L.-	Colchester Lowland.
C. R.-	Cornwallis River.
Cu. L.-	Cumberland Lowland.
G. V.-	Gaspereaux Village.
P. E. I.-	Prince Edward Island.
SH. R.-	Shubenacadie River.
S. N. B. H.-	Southern New Brunswick Highlands.
W. N. B. H.-	Western New Brunswick Highlands.

Cretaceous peneplain - cross-lined. (Broken lines indicate a doubtful extension of the Cretaceous peneplain)
Tertiary peneplain - areas left blank.

The following Publications of the Museum of Comparative Zoölogy are in preparation: —

Reports on the Results of Dredging Operations in 1877, 1878, 1879, and 1880, in charge of ALEXANDER AGASSIZ, by the U. S. Coast Survey Steamer "Blake," as follows: —

E. EHLERS. The Annelids of the "Blake."
C. HARTLAUB. The Comatulæ of the "Blake," with 15 Plates.
H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea of the "Blake."
A. E. VERRILL. The Alcyonaria of the "Blake."

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of ALEXANDER AGASSIZ, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

Illustrations of North American MARINE INVERTEBRATES, from Drawings by BURKHARDT, SONREL, and A. AGASSIZ, prepared under the direction of L. AGASSIZ.

LOUIS CABOT. Immature State of the Odonata, Part IV.
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" On Arachnactis.
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Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieutenant Commander Z. L. TANNER, U. S. N., Commanding, in charge of ALEXANDER AGASSIZ, as follows: —

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" The Thalassicolæ.
C. CHUN. The Siphonophores.
" The Eyes of Deep-Sea Crustacea.
W. H. DALL. The Mollusks.
H. J. HANSEN. The Cirripeds.
W. A. HERDMAN. The Ascidians.
S. J. HICKSON. The Antipathids.
W. E. HOYLE. The Cephalopods.
G. VON KOCH. The Deep-Sea Corals.
C. A. KOFOID. Solenogaster.
R. VON LENDENFELD. The Phosphorescent Organs of Fishes.
H. LUDWIG. The Starfishes.
J. P. McMURRICH. The Actinarians.
E. L. MARK. Branchiocerianthus.
JOHN MURRAY. The Bottom Specimens.
P. SCHIEMENZ. The Pteropods and Heteropods.
THEO. STUDER. The Alcyonarians.
M. P. A. TRAÜTSTEDT. The Salpidæ and Doliolidæ.
E. P. VAN DUZEE. The Halobatidæ.
H. B. WARD. The Sipunculids.
H. V. WILSON. The Sponges.
W. McM. WOODWORTH. The Nemerteans.
" The Annelids.

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AT HARVARD COLLEGE.
VOL. XXXVIII.

3189

GEOLOGICAL SERIES, Vol. V. No. 4.

AN EXCURSION TO THE GRAND CANYON OF THE COLORADO.

BY W. M. DAVIS.

WITH TWO PLATES.

CAMBRIDGE, MASS., U.S.A.:
PRINTED FOR THE MUSEUM.
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No. 4. — *An Excursion to the Grand Canyon of the Colorado.*

By W. M. Davis.

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Introduction.

In June, 1900, it became possible for me to visit the district of the Grand Canyon of the Colorado, and to see upon the ground the wonderful features of a region that had long been familiar from the reports of our governmental surveys. Our party consisted of Prof. R. E. Dodge of Teachers' College, Columbia University, Prof. H. E. Gregory of Yale University, Mr. R. L. Barrett of Chicago, Mr. Richard Wetherill of Pueblo Bonito, N. M., Dr. Tempest Anderson of York, England, and the writer. We reached Flagstaff, Arizona, by the Santa Fe Western Railroad on June 3, spent twenty-three days travelling irregularly across country, and went out from Milford, Utah, to Salt Lake City by a branch of the Oregon Short Line on June 26. Our itinerary is shown on the accompanying outline map, Figure 1, with dates of camps, and in the list of camps given below. We travelled partly in wagon, partly on horseback, and averaged about twenty-five miles a day. The clouds of thunder showers were frequently seen in the distance, but we had rain only twice; first a few drops in the canyon, June 7, and next a brisk shower near the Little Colorado crossing on the morning of June 10; the centre of this shower passed north of us, and the muddy streams from its short-lived down-pour met us as we were ascending a dry arroyo, or "wady." Many days were almost cloudless and oppressively hot over noon. The nights were cool, with the exception of one that we spent near the bottom of the canyon, which was unpleasantly warm. A brief report upon our trip has already been published in the "American Journal of Science," for October, 1900.

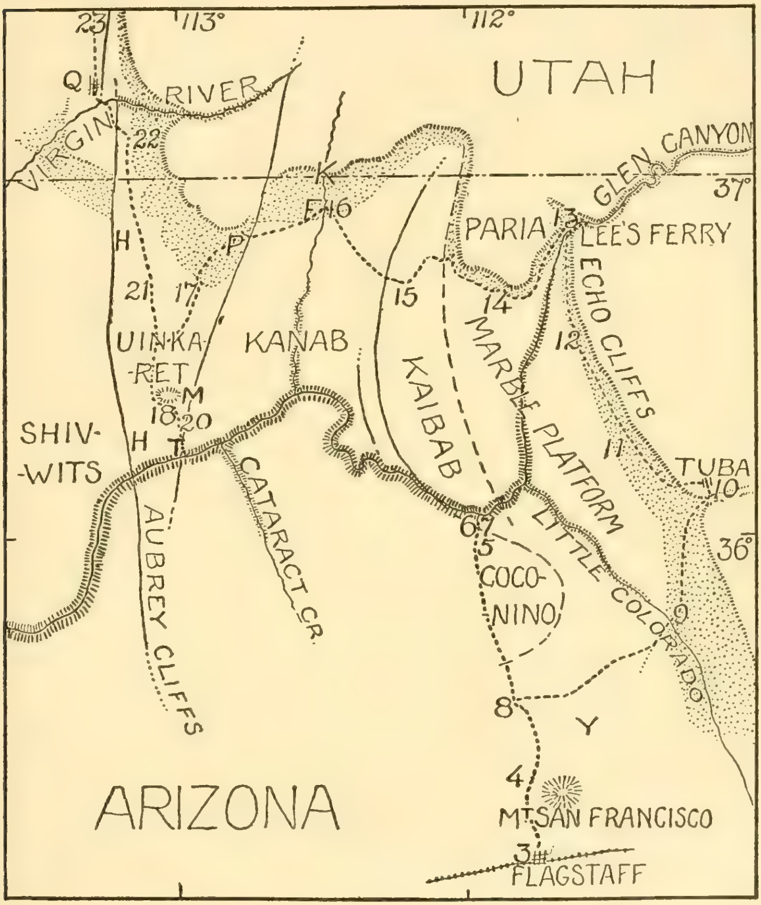
23
113°
112°
UTAH
Q
VIRGIN
RIVER
22
K
F
16
GLEN CANYON
37°
PARIA
13
LEE'S FERRY
ECHO CLIFFS
H
P
21
17
15
14
12
UINKA-
-RET
KANAB
KAIBAB
MARBLE PLATFORM
M
18
20
SHIV-
-WITS
H
T
CATARACT CR.
11
TUBA
10
6
7
5
36°
COCO-
NINO
LITTLE COLORADO
AUBREY CLIFFS
9
8
Y
4
MT. SAN FRANCISCO
3
FLAGSTAFF
ARIZONA

FIGURE 1.

Route-map of Grand canyon district. The dotted belt represents the weak lower Triassic and Permian strata separating the mesozoic area on the northeast from the palæozoic area on the southwest. The several blocked plateaus are separated by faults (continuous lines) or flexures (broken lines). The route followed is marked by a fine broken line, with numbers to indicate dates of camps in May, 1900. F, Fredonia; H, H, Hurricane ledge and fault; K, Kanab; M, Mt. Trumbull; P, Pipe spring; Q, Toquerville; T, Toroweap valley; Y, recent lava mesa. Outline taken from Dutton's Atlas.

ITINERARY. — June 4th, 1900, Flagstaff northward to Stokes spring, at northwest base of San Francisco mountain; 5th, northward to the Coconino forest, within four miles of Hance's on the canyon rim; 6th, descended from Cameron and Berry's Hotel by Grand View trail into canyon and spent the night at the level of the lower Tonto shales; 7th, returned to Cameron and Berry's; 8th, southward to Hull's spring on road to Flagstaff; 9th, northeastward to Little Colorado river at crossing of road from Flagstaff to Tuba; 10th, northward to Tuba; 11th, northward along base of Echo cliffs to Cottonwood tanks; 12th, still northward along Echo cliffs to Tanner's tanks; 13th, still northward along Echo cliffs, crossing the Colorado river at Lee's Ferry; 14th, southwest to Jacob's pools under the Vermilion cliffs of the Paria plateau; 15th, west to Jacob's lake on the Kaibab plateau, 16th, northwest to Fredonia; 17th, westward to Pipe spring and southwestward to Yellowstone spring near Antelope valley; 18th, southwestward to Trumbull spring at southern base of Mt. Trumbull;[1] 19th, ascended Mt. Trumbull, then southward to Oak spring; 20th, southward to Vulcan's throne in the Toroweap, and back to Oak spring; 21st, northward to Clay holes; 22nd, northward to Gould's (Workman's) spring; 23rd, northward past Toquerville to Kelsey's ranch; 24th, northward past Cedar City to Rush lake; 25th, northwest to Minersville; 26th, northwest to Milford; night train to Salt Lake City.

SUMMARY OF PREVIOUS WORK. — An account of new observations made in such a district as that of the Grand Canyon of the Colorado, already well studied by the explorers of our western surveys, naturally lays more emphasis on novel interpretations of former observations or on subordinate matters newly observed, than on the great structural features of the region or on the principal events of its history. But whatever of novelty is now to be gleaned in that marvellous region must rest so immediately on the work that has been already done there that I wish at the outset to express the great indebtedness that all of our party felt to the pioneer work of Newberry, Powell, Gilbert, Dutton, and Holmes, whose labors have transformed a desert wilderness into classic ground for the geologist, and whose reports are quoted whenever it is desired to illustrate all that is marvellous in the way of displacement and denudation. The topographical maps prepared by Bodfish and Renshawe in 1879 are also of great service to the traveller. The main conclusions of the earlier explorers are not to be disputed. The great unconformities at the base of the plateau series, the enormous volume of nearly horizontal and conformable strata from lower Palæozoic to Tertiary, the division of the region into great blocks by displacements, either faults or flexures, trending about north and south, the great denudation by which the plateaus bordering the canyon have been stripped of thousands of feet of strata, the sharp erosion by which the canyon has been incised in the plateaus, and the superb development of volcanic phenomena, — all these great features are standard examples for citation. There are, however, certain subordinate conclusions announced in the earlier reports which seem open to question, and it is chiefly to a consideration of these debatable points that the present essay is devoted.

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[1] Trumbull spring is on the slope of the mountain several hundred feet above its base: at the time of our visit it gave very little water. The place is not to be recommended as a camping ground. Oak spring, four miles further south, is much better.

The following brief summary of certain aspects of the work of three earlier observers may be of service to the reader.

Newberry, geologist of the Ives expedition to the Colorado river of the west in 1857–58, ascended the Grand Wash cliffs to the plateaus from the deserts among the Basin ranges on the south of the river, descended northward into the Grand canyon near its western end by the side canyon of Diamond creek, and, ascending again, traversed the southern plateaus past San Francisco mountain from west to east. He recognized the fundamental crystalline rocks beneath their heavy unconformable cover of palæozoic strata (pp. 54–58); he perceived the importance and efficacy of ordinary erosive processes not only in the excavation of the narrow canyons beneath the plateaus by the larger and smaller streams (pp. 45, 46), but also in the broad recession of the cliffs upon the plateau (pp. 45, 62), indeed he regarded the opening of the broad upland valleys on the plateaus, such as that of the Little Colorado, as "a much grander monument of the power of aqueous action than even the stupendous cañon of the Colorado" (p. 86). He noted a "slight arching of the strata" in passing from what we may now call the southern Shivwits to the southern Uinkaret plateau (p. 58), and a "curve of the underlying rock" on descending from the Coconino plateau (south of the Kaibab) to the platform of the Little Colorado valley (p. 61); but he denied the occurrence of other displacements, not only in the canyons but also along the north-south escarpments, saying that "the strata of the table-lands are as entirely unbroken as when first deposited" (p. 46); and this is not unreasonable when it is remembered that his route led him across the southern plateaus where the great displacements weaken and disappear as they come down from the north. He did not demand two periods of erosion for the sculpture of the plateaus and the narrow canyon; difference of resistance in the upper and lower strata seemed to him to account for these contrasts in the amount of destructive work (p. 62), but he inferred a more active erosion in former times than at present; "everything indicates that the table-lands were formerly much better watered than they now are" (p. 47, also pp. 62, 76).

Powell in his adventurous expedition down the canyon (1869) and in his journey over the northern plateaus (1870), discovered the double unconformity in the Kaibab section of the Grand canyon (*a*, pp. 212, 213), gave many new details concerning the rock series, and emphasized the production of the canyons by erosion in his announcement of the "antecedent" origin of certain rivers (p. 163). He presented a clear account of the great displacements by faults and flexures which divide the Grand canyon district into huge "blocks," trending north and south (*a*, pp. 185–190, Figure 73), as well as of the great cliffs of erosion or retreating escarpments, north of the canyon, facing south and trending irregularly east and west (*a*, pp. 190, 191, Figure 74); "the cliffs of erosion are very irregular in direction, but somewhat constant in vertical outline; and the cliffs of displacement are somewhat regular in direction, but very inconstant in vertical outline" (*a*, p. 191). Powell does not seem to have felt the necessity of supposing an uplift of the region between the great denudation of the uplands and the incision of the narrow canyons (pp. 206, 213), but he states that "the carving of the cañons . . . is insignificant when compared with the denudation of the whole area, as evidenced in the cliffs of erosion" (*a*, p. 208). The date of the displacements is not very sharply defined; when the great denudation began "there were no faults and no benches" (*a*, p. 200). The first displacements occurred after the erosion of valleys had been begun, the displacements were long continued, and must have been slower than the erosion of valleys by the principal streams, for the displacements did not modify the stream courses (*a*, p. 201). "Though the entire region has been folded and faulted on a grand scale, these displacements have never determined the course of the streams. . . . All the facts concerning the relation of the water-ways of this region to the mountains, hills, cañons, and cliffs lead to the inevitable conclusion that the system of drainage was determined antecedent to the faulting and folding" (*a*, p. 198). The recession of cliffs is greater in the plateau blocks of greater uplift than in those of less uplift (*a*, p. 191). Volcanic action began with the period of displacement and continued till after the Grand canyon had been eroded (*a*, pp. 201, 94, 131); a close relation is inferred between the lines of fracture and the location of the volcanic vents (*a*, pp. 6, 94, 196). An arid climate is thought to have long prevailed, for otherwise the cliffs and canyons could not have maintained their sharp forms (*a*, pp. 204, 209, 211). Some additional details concerning the stratigraphy of the plateau series are presented in Powell's "Geology of the Uinta Mountains" (*b*, pp. 43, 54, 62, 70).

Dutton first presented his conclusions in a report on the "Geology of the High Plateaus of Utah" (1880); they were afterwards elaborated in his "Tertiary History of the Grand Canyon District" (1882). Reference is here made chiefly to those points which carry the study of the region beyond the stage reached by Dutton's predecessors. Several periods of uplift and displacement are given geological dates, but in the absence of the later Tertiary deposits, such terms as Miocene and Pliocene are used only in a general way (*c*, p. 192). One of the oldest displacements is the Waterpocket flexure, involving all strata up to and including the Cretaceous; it is crossed by the Colorado in Glen canyon, and is unconformably buried in the northwest by the horizontal Eocene strata of Thousand lake mountain, one of the high plateaus (*a*, pp. 44, 288, *c*, 215). The whole region began to rise in the early Tertiary (*a*, pp. 14, *c*, 219), and several broad gentle swells were at the same time locally elevated above their surroundings; one of these was the San Rafael swell (Miocene) north of the Henry mountains, and another of much greater size was the Grand canyon district (late Eocene, *a*, p. 19). Faults and flexures in the Grand canyon district were of later date. The whole uplifted region was greatly eroded in Miocene time, and more slowly in Pliocene time (*a*, pp. 18–21). The first chapter of erosion, frequently named "the great denudation" and placed in Miocene time, witnessed the removal of strata having an average thickness of six thousand feet from a broad area in the Grand canyon district, reducing the surface to moderate relief, "a very flat expanse" (*c*, p. 77, also pp. 119, 224). On such a surface, the volcanic eruptions which had begun at an earlier period poured forth great flows of lava; eruptions continued still later, the vents being generally independent of fault lines, even though new vents were made after the time of faulting (*c*, pp. 105, 107). The high plateaus of Utah are residual table-lands capped by Tertiary strata and lavas, remnants of the great denudation that stripped the lower plateaus on the south and east (*a*, p. 22). It was after the great Miocene denudation that the Kaibab and the Echo cliffs monoclines began to have a separate existence (*a*, p. 42, *c*, pp. 192, 205), and with these local uplifts there was also a wide-spread and sudden uplifting of the whole district in virtue of which the deep and narrow canyons of to-day have been cut (*a*, pp. 38, 45, *c*, pp. 100, 191); it is by this uplift of late date that the high plateaus of Utah have reached their great altitude (*a*, p. 23). The system of north and south faults, extending from the Grand canyon northward into the high plateaus, was closely associated with the Pliocene uplift of the region, although some of them may have begun earlier and continued later, even as late as the glacial period (*a*, pp. 27, 28, 35, *c*, pp. 94, 116, 187, 191, 226). It was during a pause in the Pliocene uplift that the esplanade of the "outer gorge" in the Kanab and Uinkaret plateaus was opened (*c*, pp. 121, 226, 227), while the inner gorge of the Grand canyon in these plateaus has been eroded since the later faulting took place (*a*, p. 37, *c*, pp. 94, 227). Although some superposed streams are found in the Water-pocket flexure, where the Tertiary strata have been stripped from it (*a*, p. 288), the water-ways are thought to be antecedent in nearly all cases (*a*, pp. 16, 17, *c*, pp. 73, 187, 204, 219); San Rafael river and Curtis creek, both of which cross the San Rafael swell, are instanced as particularly good examples of their class (*b*, p. 63). Most of the great Miocene denudation was performed in a humid climate; then there was a gradual desiccation, as a result of which a number of tributary streams disappeared in Pliocene time, leaving untrenched valley floors high above the present canyon bottom (*c*, pp. 99, 194, 201); to the surviving streams of this dry period belongs the erosion of the narrow canyons and the steep cliffs (*a*, pp. 22, 23, *c*, pp. 223, 227). A temporary return to a humid climate occurred in the glacial period, and certain ravines on the Kaibab and Paria plateaus were then carved (*c*, pp. 196, 202).

In brief, the work of denudation in the Grand canyon district seems to require two cycles of erosion: the first, initiated by a broad uplift, had advanced well towards old age under a humid climate when the second, characterized by an arid climate, was introduced by another broad uplift complicated by certain dislocations; the second was subdivided into two episodes by a pause in the uplift, the first episode having approached maturity, while the second has not passed beyond youth.

The work of other observers, chiefly Gilbert, Howell, and Walcott, will be referred to further on.

THE ROCK SERIES. — The following figure of the rock series is here introduced for the convenience of the reader. It is compiled from reports by Dutton (*a, c*) and Walcott (*d*, p. 50), to which the brief article by Frech may be taken as supplementary.[1]

The strata exposed in the canyon walls reach up to the top of the Aubrey; those in the terraces of the High plateaus reach down nearly to the base of the Trias. The weak beds of the lower Trias and the Permian, with the resistant Shinarump sandstone between them, occupy the border between the base of the great terraces and the stripped surface of the upper Aubrey which extends over so large an area of the plateaus adjoining the Grand canyon.

LOCAL NAMES, MAPS, ETC. — Our habit of accenting the antepenultimate syllable of Indian words, whose original accent is on the penult, leads to a mispronunciation of a number of names for local features adopted by Powell, Dutton, and others in the Grand canyon district. The following list compiled from various sources may serve a useful purpose in preserving something of the original sound of these words, as well as in giving their meaning, along with that of some English names: —

Aubrey: The name of an army officer, given to a valley southeast of the Shivwits canyon, and extended by Gilbert to the line of cliffs north of the valley and to the upper Carboniferous strata in the cliffs (*a*, p. 177).

Coconino: (Variously spelled Cocanini, Coanini, etc.). Name of a forested plateau south of the Kaibab (Merriam, p. 35).

Grand Wash: "In this wide valley are several lines of drainage, of which the main one . . . is called the 'grand wash.' These washes generally have the cañon form — flat, gravelly bottoms, sloping talus, and steep escarpment above" (Marvine, p. 196). The same name is applied

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[1] The name, Vishnu, given to a spur on the Kaibab wall by Dutton (*c*, p. 148) and applied to the crystalline schists in the bottom of the canyon by Walcott (*d*, p. 50), is to be regretted as out of place in the occidental world. Unkar and Chuar, as subdivisions of the Grand canyon series, Shinarump as a dividing member between the palæozoic and mesozoic series, Kaibab, Kanab, and the rest for the blocked plateaus, Toroweap and Paunsagunt for valleys, have much local flavor, however barbarous and ungraceful they may sound to our ears. But Shiva's and Vishnu's temples as names for pinnacled spurs of the Kaibab in the canyon wall, and Vishnu as a name for the fundamental rocks, buried by the plateau-making strata, are unnaturalized foreigners. The Vishnu schists in the desert bottom of the Grand canyon are as inappropriately named as Diana's baths in the cold White mountains of New Hampshire.

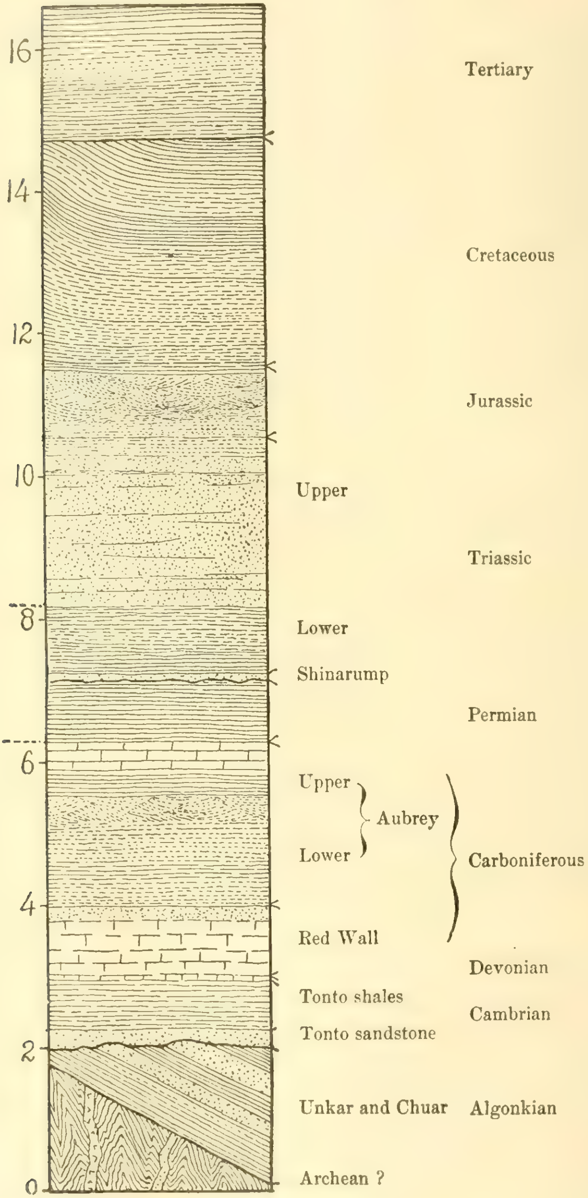
16
14
12
10
8
6
4
2
0
Tertiary
Cretaceous
Jurassic
Upper
Triassic
Lower
Shinarump
Permian
Upper
Aubrey
Lower
Carboniferous
Red Wall
Devonian
Tonto shales
Cambrian
Tonto sandstone
Unkar and Chuar
Algonkian
Archean ?

FIGURE 2.
Columnar section of formations in the Grand canyon district.

to the fault beneath the valley floor and to the great cliffs of the Shivwits plateau bordering the valley on the east.

Hurricane Ledge: "It is related that a storm overtook a party of Mormon officials while attempting to explore a route for a wagon road up a gulch which comes down from the upper country, and hence its name" (Powell, *a*, p. 187). The same name is given to the fault which determines the "ledge" or cliffs along the western border of the Uinkaret plateau.

Kaibab: "Mountain lying down" (Powell, *a*, p. 185). The highest plateau bordering the Grand canyon.

Kanab: "Willow" (Powell). Name of a tribe, a creek, a plateau, a canyon through its middle, and a town on the creek.

Paría: "The Ute name for elk" (Dutton, *a*, p. 253). A Triassic plateau east of the Kaibab, and a creek and canyon in it.

Shinárump: "Capping the cliffs, we find conglomerate, over which are scattered many fragments of silicified wood, known to the Indians as the arrows of *Shin-au′-av*, or *Shin-ar′-ump*" (Powell, *a*, p. 190). "The weapons of Shinav, the wolf-god" (Dutton, *a*, p. 147). A conglomeratic sandstone at the bottom of the Trias.

Shi′-vwits: Shiv signifies spring; Shivwits, the people of the springs (Powell). This word is spelled Shiwits, Sheavwits, Scheavwits, in various reports; the spelling here adopted being given by Powell (*a*, p. 128). The westernmost of the blocked plateaus.

Tonto: Spanish name of an Indian tribe, meaning "fool;" given by Gilbert to the basal sandstones of the Palæozoic series.

Toro′weap: "A clayey locality" (Dutton, *a*, p. 30). The valley between the Uinkaret and Kanab plateaus, probably so named from the fine silt deposited on the valley floor back of Vulcan's throne.

Uinka′ret: "Pine mountains" (Powell, p. 199). One of the blocked plateaus, capped with many volcanic cones and flows.

The chief features of the district are shown on eight sheets of the topographical map published by the United States Geological Survey: St. Thomas and Camp Mohave, Nev., Mt. Trumbull, Kaibab, Echo cliffs, Diamond creek, Chino, San Francisco mountain, Ariz.

Geological maps are given in Dutton's reports on the High plateaus and on the Grand canyon.

The drawings from which the illustrations of this article are reproduced can make no claim to accuracy of detail. They are made up from hasty sketches in which but little more than an outline was recorded. They err, as a rule, towards too great regularity of structural features, as in the view of Vermilion cliffs of the Paria (Figure 5). As a whole, they are diagrams rather than pictures.

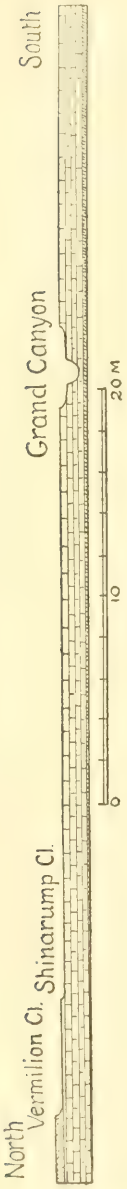

FIGURE 3.

North-south section through Kanab plateau; vertical and horizontal scales about the same. Reduced from Dutton (c).

The Great Denudation.

TWO CYCLES OF DENUDATION. — Some time before our excursion I had heard doubts expressed by a competent and critical observer as to the necessity of postulating pauses in the uplift of the region in order to explain the production of the existing topography of the Grand canyon district. These doubts were based on the close association of the general surface of the plateaus bordering the canyon on the north and south, and of the floor of the esplanade, with certain resistant strata; the first with the upper Aubrey, the second with the Red wall, as indicated in Figure 3. Omitting consideration of the esplanade for the present, let us consider the possibility of producing the broadly denuded plateau and the sharply entrenched canyon in one cycle of erosion, introduced by an essentially continuous uplift, without significant pause during the movement or supplement after its close.

It is here assumed that the normal progress of erosion in a single cycle demands the relatively rapid deepening of the main valleys by corrasion, and the correspondingly early attainment of a graded slope along the valley bottoms; a weathering of the valley walls, slower at first than the deepening of the valleys but faster afterwards, yet always at a decreasing rate; an associated but on the whole a slower series of changes along the minor water-courses; and with the progress of all these processes, a gradual advance of rapidly awakening activities to a phase of maximum development, followed by a much longer phase of relaxation and a very gradual attainment of the remote and ultimate phase of rest. The assumption of a still-stand of the land during all these systematic changes is accepted temporarily, but abandoned as soon as need be in order to meet whatever other conditions may be demanded in any particular case. The question here at issue regarding the sculpture of the Grand canyon district is between an essentially single uplift, rapid or slow but continuous, on the one hand, and two uplifts separated by a long period of denudation on the other.

It is evident that a broad denudation of the upper members of a stratified series can be contemporaneous with a narrow trenching of the lower members only if the former are relatively weak and the latter resistant. The plateau series is not so simply arranged, for among the strata that have been broadly denuded are the heavy and resistant Triassic sandstones which still stand forth in strong and steep cliffs along their line of outcrop north and east of the Grand canyon; while in the walls of the canyon, especially in the Kaibab section, there are two heavy series of relatively weak strata, the upper Tonto and the lower Aubrey, which have already retreated to partly graded slopes. The upper Aubrey limestone and sandstone and the Red-wall sandstone and limestone, to whose strength the maintenance of the plateau would have to be credited on the hypothesis of a single cycle of erosion, do not appear to possess any extraordinary resistance in excess of that of the heavy strata which make the retreating cliffs north of the canyon; and the weak members of the higher series, occupying the slopes between the retreating cliffs, do not seem to be notably weaker than the weak strata between the cliff faces in the canyon, — although exception to this statement should be made with respect to the unusually feeble blue clays of the lower Trias. Hence the canyon ought to be much wider than it is, or the northern "terraces" (cliffs) ought not to have retreated as far as they have, if the whole erosion had been accomplished in one cycle. We are thus held to the conclusion that the broad denudation of the plateaus must have been far advanced in an early cycle before the incision of the canyon was begun in a later cycle of erosion.

These considerations lend direct support to Dutton's view that there were two periods of uplift in the Grand canyon district, but it is desirable that some additional evidence of the verity of this view should be found in the shape of facts that are less immediately related to postulated conditions than are those thus far mentioned. Four groups of facts of this kind may be noted here, and a fifth will be presented in the account of the canyon in a later section.

THE MATURE VALLEYS OF THE KAIBAB AND COCONINO PLATEAUS. — The upper Aubrey limestone caps the Kaibab plateau and the high ground opposite to it south of the canyon, to which the name, Coconino plateau, has been given. Powell refers to the southern highland as a "companion, or twin plateau" of the Kaibab, but a separate name is needed for it not only because the Grand canyon is cut down between the two plateaus, but also because they are separated by a strong monoclinal flexure with dip to the northeast, of which some account will be given in a later section.

The limestone capping of these plateaus is maturely dissected. Broad-floored, well-graded valleys with gently sloping sides ramify through the uplands in the most perfect manner, presenting a maturely developed form even to their heads; and this in spite of the fact that they are nearly always dry, for the wash of waste down their sides and along their floors is accomplished only during the rains and thaws of winter and the occasional showers of summer. It was of the southern or Coconino plateau that Newberry wrote: "The surface has been considerably modified by erosion, and now presents many broad and shallow excavated valleys" (p. 58). Dutton describes the Kaibab plateau as undulating "with rolling hills and gently depressed vales." The valleys are open-floored with gentle descent; they are innumerable, covering "the whole broad surface of the plateau with an infinite network of ramifications" (*c*, pp. 131, 134). Our party saw these well-established drainage ways both north and south of the main canyon, and we were much impressed with the maturity of their graded sides and floors, in contrast to the youthful expression of the precocious canyon. Plate **2** shows one of these mature valley floors in the Coconino plateau: a hill and farm of the farmer ant are in the foreground. If the upper Aubrey were so resistant as to have prevented the widening of the canyon while the heavy Triassic sandstones were stripped away for scores of miles on the north and south, no such mature valley system should be carved in the stripped Aubrey surface.

Furthermore, the contrast between the rapid wasting of the cliff in the canyon walls and the slow change of the mature valleys on the plateaus strongly suggests that the two processes represent different cycles of erosion. Dutton notes that, on the Kaibab rim of the canyon, "we often find an old ravine suddenly cut off on the brink of an abyss, and the continuation of the same ravine is seen upon the other side of the amphitheatre" (*c*, p. 170). A similar encroachment of the canyon upon the mature valleys of the Coconino plateau may be seen in the neighborhood of Hance's camp. We could also see, when looking up the canyon from the southern rim at Cameron and Berry's, that the upper Aubrey cliffs which descend into the canyon from a detached part of the Kaibab plateau that lies south of the canyon are notched by wide-open mature valleys which descend eastward with the monoclinal flexure that terminates the plateau in that direction. The valleys evidently once had a greater extension headward, but they have now lost some of their upper length by the widening of the steep-walled canyon; thus recalling the relation existing between the mature centrifugal valleys of Mt. Mazama and the sharp cliffs of the caldera that holds Crater lake in southern Oregon. It is normal enough for the deep-cut canyon to encroach upon the heads of valleys that descend away from it; but if the upper Aubrey had been resistant enough to hold the canyon narrow while the Triassic sandstones were worn away for scores of miles on either side, we should hardly expect to find beheaded valleys of a mature form; yet such a relation would be easily explained on the supposition that the beheaded valleys still retain, little changed, a mature form that they acquired in an earlier cycle of erosion, while the main river has destroyed its mature valley of the earlier cycle by incising the canyon in its floor.

THE LANDSLIDES OF VERMILION AND ECHO CLIFFS. — If the erosion of the plateaus and the canyon had been accomplished in a single cycle, there should be at the present advanced stage in the cycle no signs of revival in the processes of denudation on the retreating cliffs of the plateaus. If, on the other hand, there have been two cycles, revivals should be of frequent occurrence and of systematic distribution. The wonderful series of landslides that occur along the base of the Vermilion and Echo cliffs, on the western and eastern sides of the great notch in the Triassic escarpment that heads up at Lee's Ferry, seem to be features of this kind. It is noticeable that these slides occur relatively near the river, while further away the cliffs have a much more mature profile, entirely without slides. Inasmuch as landslides are characteristic of the earlier and more energetic stages of a cycle of erosion, it seems probable that those here described should be associated rather with the reviving activities in the youthful stage of a second cycle than with the fading activities in the advanced stage of a first and single cycle.

The neighborhood of Lee's Ferry is especially interesting in this connection. Here the Carboniferous strata of the Marble platform[1] dip gradually northeastward and descend below the level of the river, and the removal of the weak Permian and lower Triassic strata causes the valley to widen thereabouts, so that it loses the canyon form that is so marked further up-stream in Glen canyon, where the river cuts the heavy Triassic sandstones, and farther down-stream in Marble canyon, where the river has reached the resistant Carboniferous sandstones and limestones. Had the river cut down its channel continuously in a single cycle of erosion, the retreat of the Trias on either side of the notch in

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[1] It seems permissible in the interest of brevity to speak of this plateau as the "Marble platform," instead of as the "Marble canyon platform." In the same way, the Echo cliffs monocline will be called the Echo monocline.

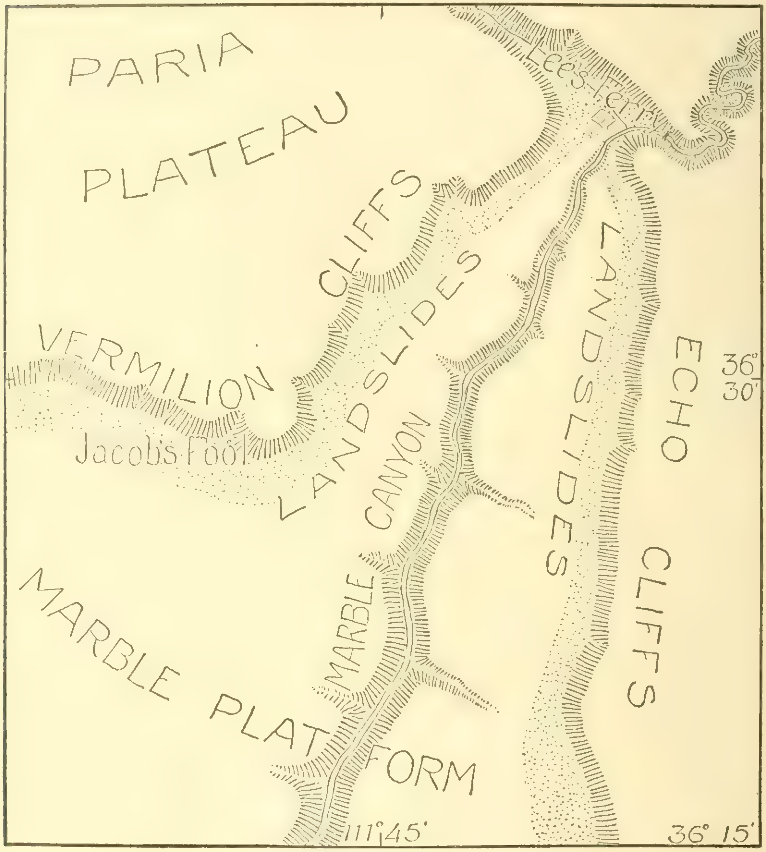
PARIA PLATEAU
Lee's Ferry
CLIFFS
VERMILION
LANDSLIDES
Jacob's Pool
CANYON
LANDSLIDES
ECHO
36°
30'
MARBLE
MARBLE PLATFORM
CLIFFS
111°45'
36° 15'

Figure 4.

Sketch map of the landslide district, southwest of Lee's Ferry. Triassic escarpment, hachured, above Permian belt, dotted. Reduced from Dutton's Atlas.

the Triassic escarpment should by this time have given the bordering cliffs — Vermilion on the west, and Echo on the east — a relatively stable profile, such as they usually have elsewhere; but as a matter of fact, it is precisely in the notch of the escarpment that the cliffs are most unstable and that landslides are most numerous. The cliffs have not retreated here far enough to allow the weak underlying strata — especially the blue clays of the lower Trias — to be concealed beneath a graded slope; it is because the cliffs are sapped by the rapid removal of the clays that the landslides result. Yet twenty miles northwest of the river, in House-rock valley between the Kaibab and Paria plateaus, a graded basal slope is well established beneath the cliffs and no slides occur. The same is true along the foot of the Echo cliffs, twenty miles south of Lee's Ferry; the weak blue clays are there concealed under a well-graded monoclinal valley floor, and slides are wanting. It is only as the river is approached that the clays are laid bare, and that, with

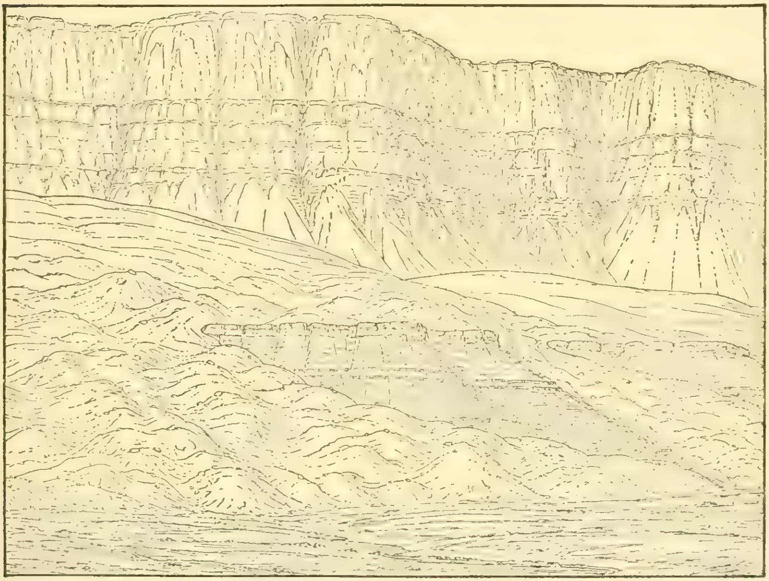

FIGURE 5.

Landslides of Vermilion cliffs. The Triassic cliffs rise to the rim of the Paria plateau. Monoclinal slides lie on the Shinarump bench, one of whose promontories is seen in the centre and another on the right, half smothered in tumultuous slides that descend to the plain of Marble platform in the foreground. Drawn from rough sketch.

their appearance, huge landslides become abundant. Just the reverse relations should obtain if the erosion of the region had been accomplished in a single cycle.

Imposing as these landslides are to one who follows the road along the base of the cliffs, they must be considered only as subordinate details among the colossal cliffs and platforms of this large-featured region, for no mention of them is found in the reports of Powell, Gilbert, and Dutton, although all these observers describe the Triassic escarpment from which the slides have slipped down. Some further account of them may therefore be given here.

In the Vermilion cliffs of the Paria plateau bordering the northern or middle part of House-rock valley, the upper members of the Triassic sandstone retreat somewhat, leaving the lower members to stand forth in a bench, and thus making two steps of mature expression in the descent from the plateau to the valley. Here the blue clays of the lower Trias and the underlying weak Permian layers are all concealed beneath the washed alluvium of the graded valley floor. If one looks down on the valley from the heights of the Kaibab on the west, an axial arroyo is seen to separate the wash of red Triassic waste on the east from that of gray Carboniferous waste on the west. In the southern part of the valley near House-rock spring, the blue clays begin to appear, and at once the lower bench of the cliffs breaks down here and there in normal landslide form; that is, the gentle dip of the cliff-making strata in the Paria plateau is steepened in the slide, so that the fallen mass takes the form of a ridge, more or less shattered and disordered, yet with a monoclinal structure apparent enough; the back slope of the ridge descends to an uneven depression along the base of the refreshed cliffs, while the outcropping face of the ridge descends to a confused mass of jumbled mounds in which the weaker basal strata are greatly disordered. The monoclinal slides become more nearly continuous and gain a formidable volume near the southern corner of the Paria about Jacob's pool; the harder strata that once formed the lower bench of the cliffs have here dropped down several hundred feet; but their forward movement is much greater, often being the better part of a mile. Passing around to the southeastern face of the Paria, the lower part of the cliffs consists of Permian strata, and the Shinarump sandstone (base of Trias) caps a conspicuous basal bench and cliff, splendidly carved. Here the slides are of two types. If their forward movement does not carry them over the edge of the Shinarump bench, they preserve the relatively orderly monoclinal form already noted; but when the slides advance far enough to fall over the bench, they flow down its frontal slope and sprawl out on the platform beneath like gigantic lava floods, as in Figure 5. The streams of rock-waste sometimes descend by a re-entrant notch in the front of the bench, like the lava flows in the notches of the upper Aubrey cliffs on the west side of Toroweap valley; they sometimes advance in large volume and cascade over the front of the bench, smothering salient as well as re-entrant of the Shinarump. The different colors of successive strata are normally arranged in orderly bands on the face of the cliffs; reddish gray sandstones at the top, then red-and-yellow-brown sandstones — vermilion seemed to us too strong a name for these cliffs, and "freight-car red" was suggested as a substitute — blue in the lower Triassic clays, chocolate brown in the Shinarump cliff, and banded creamy gray in the upper Permian slope. Something of banded colors may still be seen in the slides that have moved down and forward in orderly fashion to form the monoclinal ridges, but the color bands in the slides of greater forward advance become greatly confused when the slides sprawl down the Shinarump bench, and a most curious patchwork of reds, yellows, blues, grays, and browns is the result. Most of the slides seem to be old enough to have suffered some erosion since their descent, yet they are young and large enough to be very conspicuous elements in the landscape. They are easily recognized when seen at a distance of eight or ten miles from the summit of the Kaibab, where the road crosses it westward from House-rock spring.

If we now cross the river and go some twenty miles south of Lee's Ferry, the blue clays are concealed under the evenly graded floor of a monoclinal valley that follows the foot of the Echo cliffs: the Shinarump sandstone rises on the western side of the monoclinal valley, so as to overlap the eastern part of the Marble platform. The Triassic sandstones are, however, bolder in this part of the Echo cliffs than in the Vermilion cliffs of the northern part of the House-rock valley; they here expose a larger proportion of bare rock cluttered over with scanty and very coarse waste, not of orderly enough arrangement to be called a talus. Passing northward towards the river, the Shinarump sandstone crosses the valley obliquely as a low ridge, thus shifting from a cuesta-like attachment on the border of the Marble platform to a basal bench and cliff at the foot of the Echo cliffs; at the same time, the monoclinal valley shifts from the blue clays of the lower Trias to the weak Permian strata. Thus the blue clays come to outcrop on the slopes beneath the red sandstones of the Echo cliffs, and at once the landslides begin.

They are not so large or so numerous as those by Jacob's pool in the cliffs of the Paria, but they are of perfectly similar development when they occur. At first only forming monoclinal ridges above the Shinarump bench, they soon sprawl forward and downward on the broad platform beneath the bench. Among many others, one sprawling slide that advances at least a mile is a very striking feature to the traveller who follows the monoclinal valley road northward towards Lee's Ferry. When first seen at a distance of eight or ten miles, the slide seems to be a varicolored ridge or spur, stretching forward in abnormal position from the base of the Shinarump bench; on a nearer view, its origin is evident enough, and when seen from in front, so that its full breadth is recognized, its lower part takes the form of a huge paw, below a wrist that is narrowed at the fall over the bench. We did not recognize any wrinkles ploughed up in front of the slides, such as Russell has described in association with certain great landslides in Washington (b. 47).

All this seems inconsistent with the scheme of one cycle of erosion, but perfectly consistent with the scheme of two cycles: the first having witnessed the development of a floor of weak Permian and lower Trias over the northeastern part of the Marble platform, with a border of maturely stable cliffs of Triassic sandstones on the north and east; the second having witnessed the incision of the Marble canyon, along with which came a rapid removal of the weak Permian strata down to the more resistant Carboniferous members, and with this an accelerated recession of the Triassic cliffs in the Lee's Ferry angle. It may be well to say again that the "scheme of one cycle" is an essentially single and continuous uplift, during and after which the denudation of the region has been accomplished in a single and persistent effort of the destructive forces; while the "scheme of the two cycles" involves two uplifts separated by a pause of relative quiescence, during which the great denudation of the plateaus was well accomplished; the incision of the canyons, the removal of weak strata from the denuded plateaus, and the revival of certain activities, such as have just been described, being the result of the second uplift.

THE MIGRATION OF CERTAIN DIVIDES. — Among the minor evidences of a modern revival of erosion, mention may be made of two examples of migrating divides in localities where a stable water-parting might have been expected if the erosion of the region had been accomplished in a single cycle.

Divide near Pipe Spring. — One example of this kind lies in the weak lower Triassic area west of Pipe spring and south of the Vermilion cliffs. It is crossed by the road leading from Kanab and Fredonia to St. George. The divide does not here separate well-defined valleys, but marks the boundary between two long and broad graded platforms of gentle declivity, one slowly descending eastward and southeastward to Kanab creek, the other westward to a dry branch of Virgin river.

The eastern platform heads westward in a sharp slope or "wall" of weak lower Triassic shales, two or three hundred feet high and locally carved into bad-land spurs, forming a great westward curve, as if a large bight had been gnawed into the head of the western platform, whose border is appropriately concave. Evidently the eastern slope is gaining area by undercutting the western. When we saw first this wall on looking west from Pipe spring, it was perplexing, as there was no structure known in the lower Trias by which it could be explained; and moreover its even profile, descending gradually to the south, bevelled the gentle northern dip of the strata in a curious fashion (Figure 6). But later in the day, when we looked northward to the divide from a point on the road between Pipe spring and Mount Trumbull (S, Figure 6), the origin of the wall was easily discovered. The two graded platforms were then seen in opposing profiles, the eastern heading under the western, as in Figure 7. Indeed, the northern part of the western platform could be seen to extend several miles eastward around the head of the eastern platform, forming a bench that obliquely ascended the front of the Triassic cliffs independent of structural guidance, until it must have been a good thousand feet above the eastern platform. I have never seen so fine an example of the relation between two drainage slopes, one encroaching on the other. It was a disappointment that our hurried movement made closer study of this area impossible.

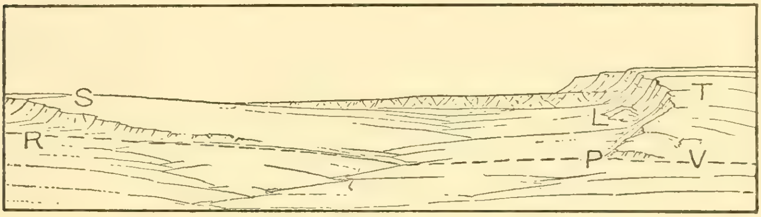

FIGURE 6.

View from east of Pipe spring, showing "wall" of migrating divide in the background. P, Pipe spring; T, Triassic plateau; L, landslide; S, Shinarump mesa; V-R, Sevier-Toroweap fault-line. Constructed from map and sections.

It is noteworthy that here, as in the neighborhood of Lee's Ferry, landslides have taken place where the blue clays have been uncovered by the encroachment of the eastern platform on the base of the Triassic cliffs. This was the case just west of Pipe spring, where the former head of the western platform has been deeply undercut. The blue clays were seen here and there along the base of the refreshed cliffs, and several landslides were noted in the same small district (L, Figure 6).

Relation of the Pipe Spring Divide to the Pipe Spring Fault. — Another peculiar feature of the eastern platform near Pipe spring is that it crosses the line of the Sevier-Toroweap fault (see that section) with unbroken grade, and that its descent is against the heave of the fault; that is, from the relatively depressed block of the Uinkaret to the relatively uplifted block of the Kanab plateau. No topographic indication of the fault is preserved at this locality, because the weak lower Triassic shales on the west are brought against the weak Permian shales on the east. The obliteration of the fault, as far as the relief of the surface is concerned, is an unusual feature of the plateau region, according to Dutton; for while he noted the obliteration of the Shinarump escarpment in the neighborhood of Pipe spring (*c*, p. 80) he did not connect its disappearance with any dislocation, and he elsewhere remarked that "every fault in the district is accompanied with a corresponding break in the topography" (*c*, p. 130). It should be stated that we identified the geological formations mentioned here and elsewhere entirely by their location, their lithological features, and their succession, as described in Dutton's reports, which in this way, as in so many others, were of the greatest service at every turn. Most of the formations are

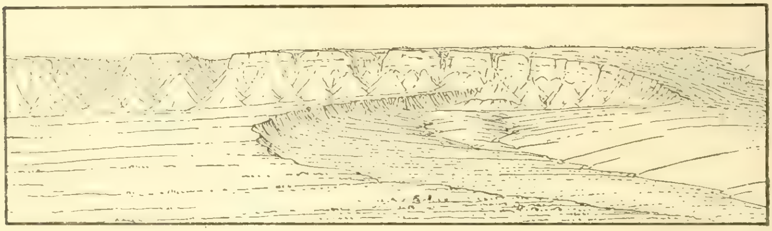

FIGURE 7.

View north near Pipe spring. Vermilion cliffs of Triassic plateau in background; the eastward dip of strata toward the Sevier-Toroweap fault-line is seen on the right, Pipe spring being near the end of the cliffs. The "wall" of the migrating divide sweeps through the middle of the landscape. Drawn from a sketch.

astonishingly bare of fossils; we saw only an occasional Productus in the limestones of the Kaibab.

The migrating divide between the two platforms near Pipe spring seems to indicate a recent and active revival of a contest that should, in a single cycle of erosion, have been settled long ago, but that might, on the other hand, be still in progress in the present youthful stage of a second cycle following the late maturity or the fine old age of the first. It is as if the news of the uplift that enabled the Colorado to incise its canyon beneath the plateaus had but lately reached the Pipe spring district. We may, therefore, suppose that a stable divide between the western branches of Kanab creek and the eastern headwaters of the westward drainage once existed somewhere to the east of the present unstable divide. If the stable divide were reconstituted in the position indicated for it by the remnants of the west-sloping graded platform, the east-sloping platform would necessarily stand above the level that it occupies to-day. This would demand the reconstitution of a graded Permian platform several hundred feet above the level of the Kanab plateau southeast of Pipe spring, a position that is entirely consistent with certain expectations as to the altitude of the ancient lowland of denudation produced in this neighborhood by the long-continued denudation of the first cycle of erosion, as will be shown further on. A reason for the present advantage of the eastern drainage may be found in some slight tilting associated with the uplift by which the second cycle was introduced; or it may be found in the lower stand of the resistant upper Aubrey strata in the nearly level structures of the Kanab plateau than of the same strata on the somewhat upturned western side of the Uinkaret plateau; but no decision can be announced without much more field work. The evidence furnished by this example of a migrating divide as to the date of the Sevier-Toroweap fault will be considered in connection with the fault lines.

The Cedar Ridge Divide under Echo Cliffs. — A second example of a migrating divide occurs in the monoclinal belt of the weak blue lower Trias clays already described as running along the base of Echo cliffs. The belt is followed by a wagon-road from Tuba to Lee's Ferry, first slowly ascending the graded floor of a south-discharging monoclinal valley, then slowly descending the graded floor of a north-discharging valley; the divide between the two valleys being known as Cedar ridge. The divide is, however, not a ridge in any proper sense. The southern valley undercuts the head of the northern one, and the two are separated by an abrupt southward slope, exposing the blue clays that are elsewhere completely hidden under alluvium (Figure 8). It is very clear that the southern valley is in process of being lengthened by headward growth or retrogressive erosion at the expense of the northern valley. Southward from the divide, there are terraces on the side of the deeper valley, attesting the once greater height of its floor. It was not possible for us to determine surely any local or general cause for the change that is here so actively in progress. It may, perhaps, be independent of the uplift in response to which the larger streams have cut down their canyons; nevertheless, we seem to have here as before a revival of activities that should have long since become quiescent if the erosion of the region had resulted from a single uplift.

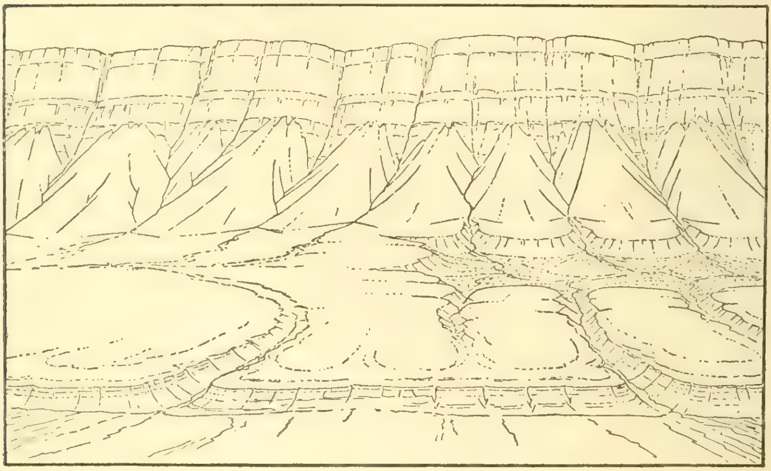

FIGURE 8.

Migrating divide at "Cedar Ridge" under Echo cliffs. The geological section here seen includes weak Permian strata under the Shinarump sandstone in the foreground; weak Triassic strata in the monoclinal valley at mid-distance, and the heavy Triassic sandstones of Echo cliffs in the background. The valley with shaded floor on right (south) is encroaching upon higher-floored valley on left (north). Constructed from field notes.

It may be that a similar migration is in progress at the divide between the northward and southward drainage of the monoclinal Houserock valley, but as this divide lay several miles north of our road we could not examine it.

Migrating Divides in Arid Regions. — It should be recalled in this connection that the migration of divides in general depends only indirectly on the action of streams; it is directly the work of weathering, creeping, and washing on the slope above the head of some deep-cutting stream. Water acts on such a slope only at time of rains and thaws. All this is strikingly illustrated in the plateau region, for here even the stream beds are habitually dry, and the whole process of rain and stream washing is intermittent and exceptional. But when the streams work, they work furiously, as is proved by the coarse stony fans of gentle slope at the ravine mouths on the flanks of the Kaibab and elsewhere. A very striking example of this kind was seen at the mouth of a ravine near the road from Flagstaff to Tuba, about ten miles southwest of the Little Colorado crossing. The ravine was sharply eroded in the sloping monoclinal surface by which the uppermost Aubrey layers descended eastward under the red shales and sandstones of the Permian; the lower ground opposite the mouth of the ravine was strewn over with huge limestone boulders that had been swept forward at time of flood.[1]

On the bare clay slope of Cedar ridge and on the red shale wall west of Pipe spring, erosion is accomplished by weathering and rain-washing rather than by stream corrasion. In spite of the aridity of the plateau climate, rain-washing is important; for the general absence of vegetation allows a single shower to effect a significant amount of work. The bare slopes retreat speedily, and the gentle grade of the valley floor or platform at the base of the slope is actively prolonged headward. The processes here at work resemble very closely those by which the recession of cliffs is accomplished: little destructive work is done on the graded platforms above or below the bare cliffs; nearly all the erosion is effected by the erosion of the cliff face and under-slope, as Dutton has pointed out (*c*, pp. 64, 221). But while cliff faces are determined by the outcrops of resistant strata, the bare slopes at the divides above described are independent of structure and are determined only by the difference of altitude of two graded valley floors or platforms. The bare slopes retreat rapidly while the graded platforms are hardly changed.

There is no reason for thinking that the average declivity of the bare slopes at these divides is notably different to-day from what it long has been or what it long will be. Hence there should be some systematic relation between the descent of waste from a bare slope and the removal of waste on the graded platform beneath; and the relation must evidently be one of equality. The slopes have been described as "bare," and so they are in a first general view, but in reality they are cloaked with somewhat loosened clay or shale, a little displaced from its normal position, still revealing the general attitude of the strata, yet masking the finer details of bedding. It must be supposed that the creep and wash of loosened waste from the slopes just suffices to keep the wet-weather streams busy when they are running in the channels on the graded floor; and hence that we here have one of the many examples of a natural equilibrium between capacity for work and work to be done. Similar examples of equilibrium probably occur between the descent of waste on certain dissected mountain slopes and the removal of the waste across the graded rock-floor platforms that stretch forward from the mountain base, as described by Penck for the subarid mountains north of Madrid in central Spain (p. 132) and by McGee for the arid mountains of the Sonoran district of Arizona and Mexico (*b*, p. 91, Plate 12). The basal angle between the slope and the platform seem to be more sharply defined in arid than in humid climates, probably because of the different values of the various agencies for soil production and removal in the two cases.

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[1] It may be noted that if the transition here noted from limestone to yellowish and red shales be taken as marking the division between upper Aubrey and Permian, then the boundary of these formations is placed about five miles too far east in this locality on sheet XXIII. of Dutton's Atlas of the Grand canyon district.

THE PERMIAN SCARPS UNDER THE SHINARUMP CLIFFS. — The comparatively small quantity of waste on the Permian scarps beneath the Shinarump cliffs of certain fine mesas in the northern part of the Uinkaret plateau suggests a recent revival in the process of sapping; for it is difficult to understand how cliffs that have receded as far as these — forty miles from the canyon — should not by this time have their under-slopes well sheeted over with waste, if the retreat had been in a single cycle. The Permian scarps are not always bare: for example, those enclosing a valley opened in the Shinarump mesa ten miles southeast of Toquerville, and extending from Sheeptrough to Workman spring (see Atlas of Grand Cañon district, sheet XX.), are cloaked with a considerable covering of waste, which here and there bears a mask of vegetation; but in this case the processes of erosion have been much delayed by a recent flow of lava on the valley floor (not shown on Dutton's map). The southern scarps of the same group of mesas, only about ten miles further south and without lava at their base, are very bare, exhibiting many delicately colored strata that maintain a horizontal course across beautifully varied spurs and ravines. The contrast between these two examples re-enforces the suggestion that the bare scarps may have been much better clothed with waste during some former pause in the activity of the erosive forces, and that their fresh exposure to-day results from a revival of these processes, such as is elsewhere manifested in landslides and in migrating divides.

The Development of Talus. — It must be confessed, however, that the development of talus-covered slopes in the arid region is a complicated problem. The quantity of talus material will vary (in so far as it comes from the capping cliff) with the relation between the thickness and resistance of the hard cliff-making strata above and the weak slope-making strata below. The texture of the talus will vary chiefly with the manner of retreat of the cliff-maker. The completeness of the talus cloak will vary with the stage of the cycle of erosion. Certain mesas, perhaps of Permian strata, seen from the Santa Fe Western Railroad, east of Winslow, have a very coarse and discontinuous talus of large slabs, derived from the strong but thin cliff-maker, which is there broken into great fragments by the rapid sapping of the weak strata in the slope. A lava-capped mesa of Permian under-slope, seen near the road between Flagstaff and Tuba about ten miles southwest of the Little Colorado crossing, has a very coarse talus. On the other hand, certain cliffs of massive red sandstone, on the line of the railroad east of Gallup, descended to the alluvial floor of their valley without any talus at their base. Dutton (*c*, p. 228) has suggested that such a relation may be explained by the burial of a normal talus under recently aggraded alluvium, thus assuming the talus to be an essential accompaniment of the cliffs. In the example east of Gallup, the absence of weak basal strata and the habit of massive sandstones to weather by crumbling, rather than by breaking into blocks, seemed to be at least as important factors as the accumulation of alluvium. That some cliffs are habitually free from talus is recognized by Dutton in his account of the Jurassic escarpment flanking the high plateaus: here "a notable feature is the absence of talus; or, if it be present, its very small proportions" (*c*, p. 36). What has been said in the section on the migration of divides regarding the retreat of bare slopes does not particularly apply here, because in the examples now under consideration, the scarps of weak strata are capped by harder strata; and the habit of such strata is to conceal themselves under a cloak of waste from their capping cliffs. Even in scarps of so small a measure of retreat as those in the Grand canyon, the weaker strata are often largely cloaked with talus, as is the case with the great slopes of the upper Tonto series in the Kaibab section, and in the slopes of the lower Aubrey that descend to the esplanade in the western part of the Kanab section. It is true that the Permian scarps of the northern Uinkaret are long, being from three to five hundred feet in relief, and that the Shinarump cap may be only fifty or a hundred feet thick. Nevertheless, the occurrence of considerable sheets of talus on the scarps in the valley east of Workman spring serves to show first that the Shinarump capping yields sufficient material to form a cloak; secondly, that the cloak will quickly accumulate if erosion is retarded at the base of the slope; and thirdly, that aridity of climate cannot account for the absence of talus on the bare scarps a few miles further south. Hence it seems that the bareness of these Permian scarps must be explained by the recent removal of a talus that once covered them.

Perched Boulders. — There are certain details connected with the problem of retreating escarpments that are finely illustrated southwest of Lee's Ferry, where the full height of the Permian scarps with their Shinarump capping is revealed. Here, as on the Uinkaret, the scarps are bare; the bareness is appropriate to the active recession of the scarps already indicated by the landslides of this neighborhood. Another item was noted. We frequently saw large blocks of sandstone, ten to thirty feet in diameter, evidently derived from the cliff above, and now perched on pedestals of weak shale a little distance forward from the base of the scarp, as in Plate 2. The perched blocks correspond to rock tables on glaciers. The pedestals are from three to fifteen feet in height; some of the blocks have lately fallen to one side, and the pedestals that once supported them are not yet wholly worn away. The top of the pedestals represents the height of the graded platform at the base of the scarp when the block rolled down from above. Since then the platform has been degraded by the height of the pedestals; at the same time, the scarp has been pushed back a decidedly greater amount, and at a rapid rate compatible with the absence of a talus cloak on its slope.

Spurs and Ravines. — The minute morphology of the carved scarps affords a pleasing study; it is a subject of subordinate importance, truly, yet perhaps as deserving of careful attention as the morphology of the leaves of plants. Where the mesa scarps have a straight front, the ravines descend in relatively direct and parallel courses with few branches. Each main ravine receives the waste from but a small length of cliff front above. The spurs are correspondingly simple, each one descending with little variety of form from top to bottom of the scarp, although with increasing relief downwards. But where a curved reentrant occurs in a mesa front, the ravines converge more or less distinctly towards the base of the scarp; several upper branches may unite in a single lower trunk, and thus the lower ravine receives the waste from a considerable length of cliff face; at the same time, many spurs fail to reach the base of the scarp, but terminate acutely between the forking ravines, as in Figure 9. On the other hand, where a projecting scarp or promontory stands forth, the ravines diverge, and a single spur at the top of the scarp may broaden and repeatedly divide in its descent, assuming a sprawling paw-like form, and including many short ravines that begin within it. Variations of this kind are repeated systematically over and over again in the Permian scarps. When the entire height of the spurs is only some four hundred feet, it may be hardly worth while to develop any special terminology for their different forms; but when one finds that very similar spurs with heights to be measured in thousands of feet occur on the dissected slopes of Mt. San Francisco, the value of a simple terminology becomes more apparent.

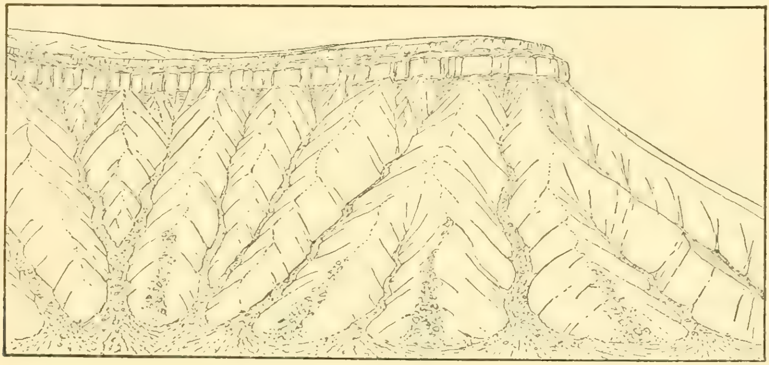

FIGURE 9.

Diagram of Permian spurs under Shinarump cliff. Tapering spurs on the left, split spurs on the right. Constructed from rough sketches.

There seems to be a curious alternation in the generation of spurs and ravines where a scanty or insufficient supply of resistant talus fragments from the cliff-maker is associated with an active erosion of the strata in the under-slope. As the coarse waste weeps and washes down from the cliff, it tends to avoid the spurs and to accumulate in the ravines. The bare spurs are then eroded more rapidly than the protected ravines, and thus a new ravine may come to be worn down the axis of what was a spur, while a spur stands forth where the ravine was before. A new supply of waste then gathers in the new ravine, while the older waste is in time removed from the new-made spur. Then the process is reversed. Several examples that seemed to be explainable in this way were noted on the Permian scarps east of Hurricane ledge; they are shown in diagrammatic fashion in Figure 9.

The Stripped Plateaus. — The details presented in the four preceding sections concerning mature valleys, landslides, migration of divides, and bare scarps, all support Dutton's conclusion that the plateau surface north and south of the Grand canyon was "planed down to a comparatively smooth surface" (*c*, p. 119) before the erosion of the canyon was begun; yet they can hardly be regarded as giving altogether independent demonstration of the conclusion, for some of them at least might all have arisen from some minor uplift of recent date. It is only when all of the elements of the problem are considered together, as Dutton often remarks, that a consistent explanation of the history of the region can be inferred; and then its erosion in two cycles seems essential. It is not desired to assert that two simple uplifts, separated by a long interval of perfect rest, constitute the diastrophic history of the region; but that a long period of relative rest and persistent denudation with respect to a comparatively constant baselevel occurred between earlier and later periods of uplift and dislocation. Each period of movement may have been of a considerable duration, complicated by pauses and intermittent displacements. Some of the earlier movements may have been separated by long pauses, of which no record now remains; but nothing less than a long period of relative quiescence before the last period of uplift seems sufficient to account for the great denudation of the plateaus and the narrowness of the rapidly widening canyon, along with the correlated details above described. The date of the faults, by which the plateau district is divided into great blocks, with respect to the earlier and later periods of denudation will be considered later.

The original uplift of the region, by which deposition was stopped and denudation begun, has been with good reason assigned by Dutton to Eocene time (*a*, p. 21, *c*, p. 217). The same author places the "period of quiescence" in "late Miocene or early Pliocene time" (*c*, pp. 77, 221); but in the absence of local fossiliferous deposits, by means of which the greater and lesser denudations can be strictly correlated with the geological time scale, I shall for the present use the terms, plateau cycle and canyon cycle, to name the greater and lesser periods in which the work of erosion has been performed; and so far as the events in the history of the district can be arranged in order, they will be thus dated.

Reasonable as the hypothesis of two cycles of erosion seems to be when all the facts are viewed together, it is difficult to point out representatives of the "very flat expanse" that was produced when the plateau cycle was interrupted by the uplift that introduced the canyon cycle. Dutton states that the older lavas of the Uinkaret and Shivwits plateaus cover considerable areas of Permian strata, which at the time of the early eruptions must have "constituted the general platform [of the district] in much the same way as the upper Carboniferous now does" (*c*, p. 107). Details concerning the Permian platforms are at present wanting; but if future observation shall show that they have no cap of resistant Shinarump sandstone, and that they are as level as is implied in Dutton's descriptions, then it may be fairly inferred that they were lowlands at the time of their burial under the lavas; for the Permian strata are too weak to permit of the production of a plain of erosion within their mass at a significant height above baselevel, such as might well enough occur on the upper surface of a more resistant formation. Accepting this conclusion provisionally, as the most probable one now obtainable, it is then reasonable to infer that the Permian lowland once extended far and wide, and that it was in fact part of the peneplain to which much of the region had been reduced at the close of the plateau cycle. To-day the peneplain on the Permian is preserved only where it was sheeted with lava; the Permian floor elsewhere visible north of the broad Carboniferous platform must be referred to the canyon cycle, as in the district southeast of Pipe spring. It will be an interesting matter for some future observer to inquire into the stratigraphic relation of the floors on which the older lavas rest in adjacent plateaus, in order to determine how they bear on the date of the faulting by which the plateau blocks are separated. Much more work on the ground will be needed before this elusive question can be definitely settled.

Since the uplift by which the canyon cycle was introduced, sufficient time has elapsed for an extensive removal of the weaker Permian strata from the plateau surface, wherever they lay within easy reach of the "wash" that must have been actively revived at the opening of the new cycle: "considerable masses of the Permian were then remaining, which have since been eroded," as Dutton puts it (*c*, p. 120). Even the resistant upper Aubrey strata, revealed by the stripping of their Permian cover, early in the canyon cycle, have suffered a significant amount of dissection, as seems to be the case over much of the Kanab plateau; but the dissection here is not so mature as that by which the higher Kaibab is characterized, as will be further considered later.

The graded Permian surface in the northern part of the Kanab plateau to-day may, therefore, be better explained as having been in large part newly developed with respect to existing local baselevels (such as sills of upper Aubrey at the heads of branch canyons) instead of as having been preserved with little modification since the close of the previous cycle. I am consequently inclined to dissent from Dutton's opinion that "the broad and slightly varied expanse" of the surface of denudation which "cuts the strata in such a way that the [low] hills usually consist of lower Permian strata lying horizontally, while the shallow valleys expose the Carboniferous" (*c*, p. 118) is a close representative of the broad lowland of denudation produced at the close of the plateau cycle. Truly, "the mean position of the surface of denudation is very nearly coincident with the dividing horizon between those two formations": and if "we successively visit districts considerably apart, we shall find in one of them [the southern] that the mean position of the surface of denudation is below that horizon so far that no Permian rocks appear in the hills; in the other [the northern] it is so far above it that no Carboniferous rocks appear in the valleys" (*c*, p. 118); truly also the gentle bevelling of slightly inclined strata over large areas is often accepted as evidence of peneplanation, as by Campbell and Mendenhall for the plateau of West Virginia (p. 483), and by Philippson for the plains of Russia (p. 40); but in the plateaus of the Grand canyon district another interpretation seems permissible. It should be noted that only two formations are referred to in the above-quoted extracts from Dutton's report; the lower one (Carboniferous) resistant; the upper one (Permian) relatively weak. These formations rise gently southward. The great Carboniferous platform (upper Aubrey) on either side of the canyon in the Kanab district, here chiefly under consideration, is free from Permian remnants over all those large areas whose drainage is actively tributary to the main river; while the continuous Permian cover, apart from certain large patches that are protected by lava sheets, is found only some distance north of the canyon, where the dip of the strata brings the Permian down to a level that is safe from erosion for the present, and that can be attacked only as the wet-weather streams cut deeper into the Aubrey sills on their way down branch canyons to the Colorado. Now, if the Permian were the resistant and the Carboniferous were the weak formation, or if the next overlying and resistant formation further north (Triassic) were also bevelled down to the Permian level, the bevelled surface would necessarily be regarded as a peneplain, at present uplifted and in process of dissection;

but no such conclusion seems compulsory in a case where only two formations are involved, and where the upper of the two is the weaker. It therefore seems legitimate to say that a peneplain, so far as one was developed at the close of the first cycle, lay in the Permian formation at some unknown height above the present plateau surface in the Kanab district; and that the Carboniferous platform as now exposed in the Kanab plateau is a stripped and somewhat dissected plain, with reference to whose northern margin the Permian plain of to-day is graded: the stripping and moderate dissection of the Carboniferous and the new grading of the Permian being the work of the canyon cycle. The Uinkaret and the Shivwits plateau seem to be susceptible of similar interpretation. The Marble platform also is probably to be regarded, like the Kanab and other western blocks, as a stripped structural surface. It must have been covered by baselevelled Permian and lower Triassic strata at the close of the plateau cycle, but these have been now for the most part stripped down to the upper Aubrey. In brief, the evidence for two cycles of erosion in the evolution of the existing topography of the Grand canyon district is not to be found so much in the general evenness of the great Carboniferous platform, beneath which the narrow canyon is cut, as in the great recession of the Triassic and other cliffs compared with the small width of the rapidly widening canyon, and in the minor phenomenon therewith correlated.

Dates of Displacements.

THE EASTERN FLEXURES. — Flexures appear to preponderate in the eastern part of the Grand canyon district, while faults are the chief form of displacements in the western part, as shown in Figure 10. It will be shown that there is much probability that the flexures are older than the faults as a whole, and that the displacements of both classes seem to deserve an earlier date than has been assigned to them in Dutton's reports.

The Earliest Flexures. — The Waterpocket and the Escalante flexures lie northeast of the field of our excursion, but as they are the only disturbances which have been regarded as pre-Tertiary, it is important to make some mention of them here. They involve Cretaceous strata, whose eroded edges are unconformably buried by the Eocene of the High plateaus on the northwest (Dutton, *a*, p. 43, pp. 280, 288, 294 : *c*, p. 215 ; Gilbert, *c*, p. 10). The San Rafael swell, still further northeast (Dutton, *c*, Atlas, sheet 11), is described as of Miocene date, probably because of the roughly concentric attitude of the escarpment of horizontal Eocene on the northwest with the escarpments of the swell itself (*a*, pp. 19, 20); but it nevertheless seems permissible to class this dome-like uplift with the Waterpocket and Escalante flexures as having been formed in what may be called the Cretaceous-Tertiary interval, and as having been, like the flexures, greatly eroded before it was buried by Eocene deposition. True, the unconformity thus implied is nowhere preserved, for the Eocene strata have now receded to a distance of about forty miles from the centre of the swell; but some indirect evidence for their original unconformable extension over the eroded swell is found in the small amount of adjustment of two transverse streams to the domed structures, as will be more fully stated further on.

The Kaibab and the Echo (*Paria*) *Flexures* have been described as about contemporaneous with the broad uplift that introduced the erosion of the Grand canyon (*c*, pp. 192, 205), but they seem to be of older origin if one may judge of the date of their deformation by the recession of the Triassic cliffs that stand in association with them. This is shown as follows: The Triassic (Vermilion) cliffs have retreated at least twenty-five miles around the northern end of the Kaibab since its uplifting; and the same Triassic cliffs have retreated to close coincidence with the line of the Echo (Paria) flexure since its production, from whatever irregular line of front they had previously when the strata were horizontal. But, on the other hand, the upper Aubrey cliffs, enclosing the outer gorge of the canyon in the Kanab and Uinkaret plateaus, have retreated only two or three miles since the beginning of the canyon cycle. Surely then the Kaibab arch and the Echo monocline must be older than the beginning of the canyon cycle. Moreover, Walcott has called attention to the flexure of the east Kaibab mono-

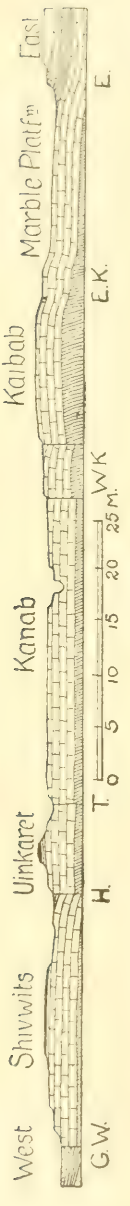

FIGURE 10.

East and west section of the Grand Canyon district, from the lower lands west of the Grand Wash fault to the Echo flexure. Vertical scale somewhat exaggerated. Modified from Dutton's section (*c*).

cline without fracture, and has concluded from this that a considerable load of overlying strata must have covered the Kaibab when the flexure was produced (*d*, pp. 60, 64); in other words, that the flexure occurred sometime before the close of the plateau cycle.

If this conclusion be correct, the crown of the Kaibab arch must have risen a thousand feet or more above a denuded lowland on the east and west at the close of the plateau cycle. The strikingly even skyline of the Kaibab, as seen from any distant point, is therefore to be regarded as indicating a stripped structural (upper Aubrey) plain, and not as a part of a once baselevelled surface, afterwards uplifted. The exposure of the arch to denudation during the later stages of the plateau cycle, as well as through so much of the canyon cycle as has yet elapsed, is indicated by the much greater dissection of its surface than that of the Kanab, which, as explained above, is best regarded as a stripped structural plain of the current cycle. The difference between the greater and less dissection of the two plateaus is indicated in Dutton's descriptions, for one is there spoken of as diversified by valleys which "cover the entire surface" (*c*, p. 134), while the other is said to be (except for deep canyons) "no more uneven than the rolling prairie of Iowa" (*c*, p. 124); and this contrast of form may be easily recognized on comparing sheets VIII. and XI. of the Grand Cañon Atlas. Another corollary of the early uplift of the Kaibab arch is that an open valley must have been eroded across it in the later stages of the plateau cycle. If this be true, then it must be further supposed that the rapid widening of the new and deep canyon in the current cycle has consumed all traces of the earlier valley.

The Crags of Echo Cliffs. — A peculiar feature of the Echo cliffs deserves brief mention. In looking along this great escarpment from the south, its crest at several points between Tuba and Lee's Ferry is seen to rise in serrated peaks with sharp slopes on the east as well as on the west, thus departing from its ordinary tabular form. We at first took the sharp serrations to indicate a local increase of dip, and on coming abreast of them were much surprised to find the dip practically unchanged from its uniformly moderate measure. The front view of the escarpment at certain points between the serrated peaks disclosed sags in the crest line that could not be explained by any local thinning of the cliff-making sandstones, for they seemed to maintain substantially a uniform thickness for tens of miles together. It was therefore suggested that the peaks and sags resulted from the occurrence of strike faults with small throw, torn on the slope of the monocline. As the retreating cliff face approaches such a fault, the crest becomes sharp and serrated, and strong eastward slopes locally replace the ordinary gentle eastward descent where faults are absent. Powell noted the sharp crags and relates them to the "line of displacement," but he did not specify the aid that local faults would give (*a*, p. 192). When the cliff face retreats still further, so as to remove the sandstones from in front of a fault plane, the crest line of the remaining cliff sags to a lower level than usual. It would be necessary to follow the crest of the escarpment for some distance in order to determine the measure of verity in this suggestion.

THE WESTERN FAULTS. — Attention may next be given to the fault lines of the Grand canyon district west of the Kaibab. These fall into the class to which Dutton gave a very late date: "None of them will go back of the Pliocene in age, and I think it probable that none of them will go behind the middle Pliocene" (*a*, p. 43). "Their formation seems to have been incidental to the uplifting of the platform which took place about the time the present Grand Cañon began to cut. . . . Before this epoch we know nothing of them" (*c*, p. 226). Some of the faults may now be considered in more detail.

The West Kaibab Faults. — Of the three faults indicated in Dutton's map along the western border of the Kaibab, we identified only the eastern one. It forms a fine wall, of generally graded slope and much scored by ravines. Its date is not easily determined, as it does not cross the cliff-making formations on the north until, according to Dutton, it joins the east Kaibab flexure. The recession of the cliff from the fault line here, as elsewhere, affords an uncertain measure of the antiquity of the faulting; for if the faulting occurred before the opening of the canyon cycle, much of the height of the present cliff may then have been fronted by weak Permian strata, since removed.

The Toroweap Fault. — The next displacement west of those which limit the Kaibab arch is the Toroweap fault. This is regarded by Dutton as for the most part of very recent date; at least part of its movement being later than the erosion of the broad-open flat-floored upper part of the canyon, called the esplanade, because the floor of the esplanade drops down to the west on passing the fault line; and later also than the eruption of a certain lava flow that was poured into the esplanade, because the lava also is dislocated by the fault (*c*, p. 94). On the latter point, I am unable to offer any evidence; but as the problem now presents itself, the dislocation of the floor of the esplanade does not seem to bear on the date of the fault; for if we regard the esplanade as dependent on structure, as will be considered further on, the break in its floor would occur at the fault line whether the fault was earlier or later than the erosion of the canyon. The small recession of the Red-wall cliffs in the Toroweap valley near Vulcan's throne (*c*, p. 94) is explainable by their relatively recent exposure in the canyon cycle, by the failure of erosion as yet to disclose any weak underlying beds, and by the protection of the base of the cliffs by lava floods, as will be more fully described further on in the section on the Toroweap. The location of this valley in close association with the fault line suggests that the fault originated before the valley was begun, that is, before the initiation of the canyon cycle; and this view is borne out by the strong recession of the Triassic (Vermilion) and Shinarump cliffs on the eastern side of what appears to be the same fault line in the neighborhood of Pipe spring. As my interpretation of the stratigraphy here differs somewhat from Dutton's, the case must be presented in detail.

The Sevier Fault Southwest of Pipe Spring. — The great Sevier fault is described and mapped by Dutton as coming southward from the High plateaus and ending near Pipe spring (*c*, p. 20), while the Toroweap fault is said to end northward at the head of the valley of the same name, twenty miles from the canyon (*c*, pp. 20, 93). A longer extension of the Toroweap fault is indicated by Powell, who briefly stated that where it "crosses the Vermilion cliffs" its throw "is only about two hundred feet;" but he does not specify that the crossing is at Pipe spring (*a*, p. 186). It happened that on our excursion we had good opportunity of seeing the general features of the Pipe spring district, where we noted that the cliffs formed on the Triassic and Shinarump sandstones were distinctly displaced with respect to what may be called the Sevier-Toroweap fault line. Hence, instead of curving the Sevier fault to the southeast and ending it near Pipe spring, as it is drawn on Dutton's map, it seems better to continue it to the south-southwest till it joins the known Toroweap fault. Where the fault-line thus extended crosses Antelope valley, a shallow depression in the broad plateau surface south of the Shinarump cliffs, its occurrence is not so easily proved as in the neighborhood of the cliffs. As indicated in Figure 11, both the Triassic and the Shinarump cliff-makers stand about ten miles further north on the heaved (eastern) than on the thrown (western) side of the fault near Pipe spring, thus indicating not only an important dislocation, but a relatively long time since its production. This is the rule of the region. Similar large measures of erosion since faulting are generally indicated by a break in the alignment of the Triassic and Shinarump cliffs wherever the fault lines cross them. Powell (*a*, p. 191), Gilbert (*a*, p. 51) and Dutton (*c*, p. 200) all recognize the greater recession of the escarpments of the heaved side of the faults as a general occurrence, but they do not explicitly connect the amount of recession with the date of faulting. The dislocation of the cliff front is, as Gilbert phrases it, "not due to any horizontal displacement along the line of fault, but merely to the fact that the eastern portions, being lifted higher than the western, became subject to different conditions of denudation" (*a*, p. 51). Near Pipe spring, not only have the cliffs of the eastern (Kanab) block receded ten miles since the faulting occurred: but ten miles is the excess of the recession of the eastern cliffs over that of the western; hence the chief movement of the fault here must certainly be of earlier date than the beginning of

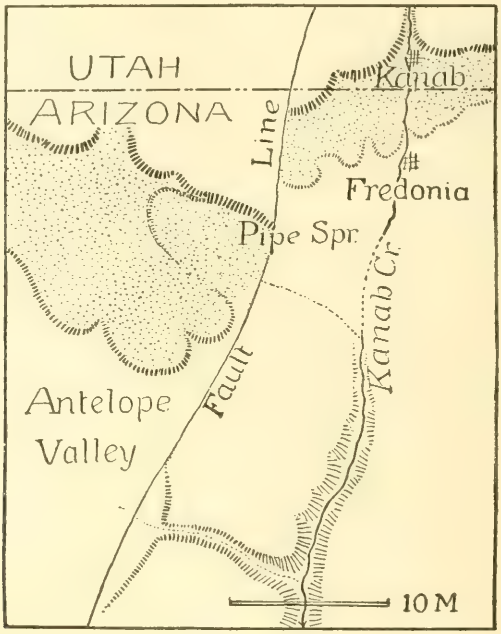

FIGURE 11.

Sketch map of the Pipe spring district, showing the Sevier-Toroweap fault. Weak lower Triassic strata, dotted; Triassic and Shinarump cliffs, hachured. Constructed from Dutton's map and original field notes.

the canyon cycle, however recent the latest of its movements may have been on the brink of the canyon.

Topographic Effects of Faulting obliterated or reversed by Erosion. — The continuously graded platform, sloping gently eastward across the fault line near Pipe spring and obliterating the topographic effects of faulting, has already been described. The fact that this platform is now gaining drainage at the expense of the west-sloping platform, strongly suggests a remote date for the displacement; had a recent movement taken place here, with uplift on the east, the westward migration of the divide could hardly be explained. A little further south, the Shinarump cliffs in the Uinkaret block, west of the fault line, overlook lower ground east of them, thus furnishing an excellent example of topographical relief standing in opposition to the displacement of the fault; evidently the result of the long action of erosion upon the unlike strata brought together by the faulting. Indeed, this part of the fault line offers many instructive illustrations of the difference between the geological and the geographical values of a fault. Geologically considered, the fault has a fixed value; geographically considered, the fault has a changing value. When the fault attains its full displacement, its geological history is completed, and its geological measure thenceforward remains constant. When the fault attains its full displacement, its geographical history is just begun, and thereafter its measure perpetually changes. The topographic features initiated by displacement may be more or less modified by contemporaneous erosion, but the young fault cliff will still be a tolerably regular feature, scored by growing ravines. Movement ceasing, erosion continues and the fault-cliff becomes lower and less regular. Where hard beds in the heaved block confront weak beds in the thrown block, the cliff consequent on faulting will last longest; where these hard beds are not underlain by weak beds (unless beneath baselevel), the cliff face will retreat most slowly from the fault line. Where weak beds are brought together, all topographical indication of the fault will soon disappear. Where hard beds in the thrown block confront weak beds in the heaved block, the topographic relief may come to contradict the throw of the fault, as is the case with the Shinarump cliffs above mentioned. But in time, all indication of the fault will be obliterated in the general reduction of the region to a peneplain, strong and weak rocks alike being laid low. If a general uplift of the region then occur, erosion may renew the fault-cliff topographically wherever strong beds adjoin weak ones, although no new movement takes place upon the fault plane. In such cases, the small retreat of the revived cliff from the fault line has sometimes given rise to the belief that the fault is of recent date, but it is evident that no such conclusion can hold. The revived cliff may be in the thrown-block, if the arrangement of the rocks favors such a result. A striking example of this kind may be seen in Tennessee (see Briceville, Tennessee, topographic sheet, United States Geological Survey), where the front of the Cumberland plateau is cut across by a northwest-southeast fault, the northeastern block being relatively uplifted; but to-day the surface is worn low on the weaker strata of the uplifted block, so that it is overlooked by the uplands of Carboniferous sandstones on the depressed block.

If these considerations are accepted, there can be little doubt that the Sevier fault continues in strong force beyond Pipe spring, as if to join the Toroweap fault, some thirty miles further to the southwest. Some topographical expression of the fault ought to be found in the broad floor of Antelope valley, beyond the Shinarump cliffs of the Uinkaret plateau, where the weak Permian of the Uinkaret block lies opposite the resistant upper Aubrey of the Kanab block. It is perhaps in this way that one may explain a west-facing bluff which extends about ten miles south of Antelope valley (Dutton, *c*. Atlas, sheet XXII.), but further study on the ground is needed before this can be assured. It is interesting to note, however, that the wet-weather drainage here is from the weaker beds of the thrown block eastward through a gorge in the bluff that is determined by the more resistant beds of the heaved block; a condition that is again entirely inconsistent with a recent movement on the fault plane.

The Hurricane Fault is not definitely dated in Dutton's report, but its southern part is thought to be of "comparatively recent origin," because "the amount of recession by erosion of the cliff of displacement is very small" (*c*, pp. 116, 117). Its northern part near Virgin river must, however, be old enough to have allowed a strong recession of the Triassic escarpment since the faulting; for the two parts of the Trias east and west of the fault line are now fifteen miles apart (*c*, pp. 42, 200); and as in the Sevier-Toroweap fault, the displacement of the cliffs is a measure not merely of their erosion since faulting, but of the excess of erosion in the heaved block over that in the thrown. The small amount of recession of the Hurricane ledge (Aubrey) from the fault line in the southern part of the Uinkaret plateau, as stated in the last quotation from Dutton, may be explained not so much by the recent date of the fault, as by the recent date at which erosion had opportunity of attacking the strata here concerned; for, as in the case of the Toroweap fault, until renewed uplift introduced the canyon cycle, it must be supposed that the strata in the Hurricane ledge of to-day were close to or even beneath baselevel, and hence out of reach of erosion. On the other hand, a branch of the main Hurricane fault cuts certain lava beds, — not the most recent ones (*c*, pp. 116, 117), — and this branch must be younger than the lavas, which in turn must at the oldest have been erupted late in the plateau cycle.

The Hurricane fault seemed to me to fade away just north of Virgin river. The line of great cliffs that comes up from the south here gives place to a monoclinal flexure, dipping to the west in sympathy with the throw of the fault; and a few miles further north the flexure loses importance, as far as we could interpret its structure in the view from the escarpment south of the river. A new displacement seemed to begin two or three miles to the west, rapidly increasing its throw northward and so continuing from Toquerville past Belleview, Kanarra, and beyond, where it sharply separates the Plateau province from the Basin range province. The southern termination of this displacement was not certainly determined. As a fault, it ends just south of Toquerville, but it may turn southwest and find a continuation in the anticline at the eastern base of Pine valley mountain. In any case it seemed entirely independent of the Hurricane fault proper. The course of Virgin river hereabouts is perhaps consequent upon the overlap of these displacements, for it lies close to the sag between them. It may be added that, although we had a fine view northward into the valley of Le Verkin creek from the rim of Hurricane ledge, we did not detect the lapse of the Permian and the unconformable overlap of the Trias on the Carboniferous, as noted by Howell (p. 285); but to assert the nonoccurrence of these features would be going too far. The neighborhood of Toquerville offers an unrivalled field for special study. The village serves as a good base of supplies, the surrounding district is traversed by many roads and trails, stratified rocks range from Carboniferous to Tertiary, igneous rocks are present in good variety, the structural features are of unusual interest, denudation has been enormous, and the half-desert scenery is superb in form and color.

The Grand Wash Fault is said by Dutton to be no older than Pliocene (*c*, p. 191); yet the work of erosion after the fault had attained a strong measure of displacement would give it a much greater antiquity, for while a monoclinal slice of the Trias is preserved along its thrown (western) side, there is no Trias on the heaved Shivwits block for fifty miles

(Dutton, *c*, p. 200, Atlas, sheet II.). The Trias must have once extended eastward beyond the line on which the fault was broken; and the uplifted eastern extension of the formation must have been worn away after the faulting. On the other hand, a late movement on the same fault line has been thus far tacitly postulated, for the uplift by which the canyon cycle was introduced in the Grand canyon district does not seem to have extended with equal strength into the Basin range province west of the Grand wash fault line. But as I have not seen this district, it must be passed only with brief mention.

The Western Monoclinal Flexures. — The above review makes it probable that, however modern certain minor movements on the fault planes may be, the chief movements, by which, as Gilbert said, the adjacent plateau blocks were made subject to "different conditions of denudation," are of considerable antiquity. They must antedate the beginning of the canyon cycle. Yet the first deformation of the Grand canyon district is of still earlier date, for the faults with heave on the east were in a number of cases preceded by monoclinal flexures with heave on the west. The few exceptions to this rule of unlike movements do not seriously invalidate it. The east Kaibab monocline is torn into an east-throwing fault near the canyon; and similar small faults are suspected along the Echo monocline, as noted above. The Escalante flexure dips to the southwest, but its displacement is gradual compared to that of the Waterpocket, Echo (Paria), and east Kaibab flexures, which all dip eastward. A flexure with strong throw on the west is indicated for the western border of the Kaibab in Powell's general section of the district (*a*, p. 190, Figure 73); the displacement given to it is as great as that of the upper of the two east Kaibab flexures. Two west-dipping flexures on the west side of the Kaibab are shown by Gilbert (*a*, p. 51); but in the more detailed descriptions and sections given in Dutton's report (*c*, pp. 183–186, Figures 3, 4, and Plate II.), nearly all of the displacement on the west side of the Kaibab is accomplished by two faults, with hardly a tract of flexure; the gentle westward dip in the western half of the Kaibab highland — more pronounced to the north where faulting is changed for a west-dipping flexure — may suffice to warrant the use of the term "Kaibab arch," but it seems to be even less pronounced than the broad Escalante flexure. Where our party descended westward from the Kaibab by one of the greater ravines, west of Jacob's lake, the horizontality of the strata all the way to the main limiting fault was in strong contrast to the pronounced flexure of the eastern border. It may be, however, that both the western faults become flexures near their northern end, as is noted for one of them, above, and as is the case with the Hurricane fault proper, just north of Virgin river. But the only flexure on the western side of the Kaibab mentioned by Dutton is one by which the thrown beds are turned down as they approach the fault plane from the west (*c*, p. 128).

The northeast dip of the flexure that separates the Coconino plateau from the Kaibab is strongly marked. Strong eastward dips are observable on the lines of the Grand wash fault and of the great fault (almost in line with the Hurricane fault) north of Toquerville. The rule that the faults throw to the west and that the flexures throw to the east is therefore very generally obeyed.

The frequent association of flexures and faults on the same line is noted by several observers. Dutton described the downward flexure of the thrown beds in connection with the Hurricane, Sevier, and west Kaibab faults (*c*, pp. 41, 113, 114, 115, 128, 185, 186); while Gilbert (*a*, p. 54) and Marvine (p. 196) give diagrams of the Grand wash fault which exhibit the same feature. Dutton suggests that flexing preceded faulting (*c*, p. 115), and Walcott discusses a remarkable pre-Cambrian fault with throw to the west, on the line of which the east Kaibab torn flexure was formed in Tertiary time, with throw to the east (*d*, pp. 49–64). It seems probable that the prevailing coincidence of flexures and fractures may elsewhere, as well as in the east Kaibab example, be associated with faults of ancient origin, possibly in the pre-Cambrian foundation of the palæozoic and mesozoic strata, although it is only in the Grand canyon that this relation is open to study.

It is certainly remarkable that the distinct flexures of the Grand canyon district dip eastward so generally, while the faults have their throw to the west with almost equal regularity. In all cases where this relation obtains, the later movement by faulting was of greater measure than the earlier movement by flexing. It is further noteworthy that the unfaulted or least faulted flexures, such as the Waterpocket, Echo, and east Kaibab, lie to the east; while the distinctly faulted flexures lie to the west. It may also be remarked that, if the difference of date here inferred for flexures and faults holds true, it will be inappropriate to use the term "Kaibab structure" in the sense given to it by Powell (*b*, pp. 14, 22), and adopted by Gilbert (*b*, p. 86); namely, as a designation for a plateau that "primarily" surmounts lower ground on both sides. The greater part of the altitude by which the Kaibab surmounts the Kanab on the west is probably not a primary feature, but a secondary one, due to faulting after flexing.

The faults have already been referred to the plateau cycle; the flexures must therefore belong still earlier in that cycle. Hence the period of the great denudation, thus far undifferentiated, should now be divided into a pre-flexure cycle, an inter-flexure-and-fault cycle, and a post-fault cycle. It is believed that a complicated scheme of this kind is much nearer the truth than the simple scheme of time division thus far postulated; but it still remains true that the post-faulting quiescent period must have been long enough for a strong excess of cliff-recession to occur in the heaved blocks, before the relatively modern erosion of the canyon was excited by a broad uplift of the region.

THE DISPLACEMENTS OF THE HIGH PLATEAUS. — Although our excursion did not lead us into the district of the High plateaus, it seems necessary to examine what has been written about them in order to see how far what has now been inferred as to the date of the faults and flexures in the Grand canyon district may find application in the adjoining district on the north. Our source of information is again chiefly in one of Dutton's reports, from which it appears in the first place that the faults of the two districts are to be considered as a single group of displacements; and, in the second place, that the uplift by which the canyon cycle was introduced probably affected the district of the High plateaus also (*a*, pp. 27, 28, 45). The faults of the plateaus are dated as younger than the youngest formations that they dislocate; namely, younger than the middle Eocene sediments and heavy lava sheets and conglomerates of a somewhat later epoch; and as old enough to have allowed a certain moderate amount of erosion since their production. The erosion on the borders of the faulted High plateau blocks seems small compared to that by which the recession of the bordering cliffs on the south has been accomplished, and Dutton therefore decides to "place the age of the principal displacements in a period which had its commencement in the latter part of Pliocene time, and extended down to an epoch which, even in a historical sense, may not be extremely ancient, and which certainly falls on this side of the glacial period" (*a*, p. 35). It seems, however, that in reaching this conclusion, no explicit consideration was given to the possibility that the faults might have occurred during a former cycle of erosion, when the district stood much lower than now; that the forms then initiated by faulting may have been much reduced or even nearly obliterated by the erosion of this earlier cycle; and that the erosion on the borders of the blocks, by which the faults have been dated, has taken place only since a general uplift has revived the erosive processes. There is some evidence that such is the case. Certain sections of the district (Dutton, *a*, Atlas, sheet 6, sections 1, 2, 3) show the Sevier plateau to consist of a heavy body of early Tertiary sedimentary strata, covered by a heavy volcanic series. This pair of rock masses ascends by an eastward rising monocline to the Fish-lake plateau, where the volcanic series has been largely removed, and even the underlying Tertiaries are reduced to much less than their normal thickness. So unequal a measure of erosion in two adjoining plateaus of similar structure suggests that the rocks of the higher one were greatly consumed during a former lower stand of the land, when the destructive processes halted at a horizon that is now found by drawing a line over the plateau tops; and that the existing valleys are chiefly the work of a revival of erosion after a broad uplift had introduced the present cycle; this broad uplift being perhaps associated with that by which the canyon cycle was introduced in the Grand canyon district. True, the displacement between the two plateaus here referred to is a flexure, not a fault; but if a former cycle of erosion is indicated by the unequal erosion on the flexed masses, it is possible that the faults which elsewhere dislocate the High plateau blocks may, as well as the flexures, have been produced in that cycle, and not in the present one. In this case, it is manifestly impossible to date the faults by the erosion that has occurred in the present cycle; they may therefore be as old in the High plateaus as in the Grand canyon district.

The relation of flexures and fractures appears to be the same in the two districts. Speaking of the High plateaus, Dutton instances three faults that are younger than the flexures which they traverse. He adds: "It is a most curious circumstance that where we find this two-period displacement the motion of the fault[1] is often reversed, — the lift of the first period is the throw of the second. It is not always so, but I believe it to be true in a majority of cases where the double movement has been detected" (*a*, p. 43). But it is of course not intended by this to imply that the High plateau flexures, which affect the Eocene beds, are as old as the Waterpöcket flexure, which was eroded and unconformably buried by the Eocene (*a*, pp. 43, 44).

Origin of the Drainage System.

General Explanation by Antecedence. — Powell classified all streams as consequent, antecedent, or superimposed (now generally called superposed). In a district where superposition seemed impossible, all streams that did not follow the dip of the strata in consequent fashion were classified as antecedent. Writing of the Colorado basin, Powell said: "All the facts concerning the relation of the water-ways of this region to the mountains, hills, cañons, and cliffs, lead to the inevitable conclusion that the system of drainage was determined antecedent to the faulting, and folding, and erosion, which are observed, and antecedent, also, to the formation of the eruptive beds and cones" (*a*, p. 198). Even certain minor streams that follow monoclinal valleys along the northern flank of the Uinta mountains were for this reason explained as having been there before the mountains were raised, and the uplift of the mountains was thought to have been too slow to displace them, in spite of their small volume (*a*, pp. 159–166). To-day there can be little question that these monoclinal streams are not antecedent but subsequent; that is, they have gained their position by headward erosion along the strike of the weak strata in which their valleys are eroded — as first explained by Jukes, who wrote nearly forty years ago, "the longitudinal valleys are of subsequent origin" (p. 400) — from time to time capturing and diverting the upper courses of such consequent streams as they encountered, and thus bringing about that remarkable adjustment of streams to structures which characterizes in so high a degree all deeply denuded regions of strong deformation.

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[1] The word "fault" is here, as in some other passages, used to include both flexure and fracture. See, for example, Dutton's account of the "east Kaibab fault" (*a*, p. 32).

Like Powell, Gilbert recognized three classes of streams, but he seems to have felt some doubt as to the generally antecedent origin of the inconsequent streams. He wrote: "A large share of the drainage of the plateaus is not consequent. How much is super-imposed and how much antecedent remains to be determined" (*b*, p. 102).

Dutton was as deeply impressed with the antecedent origin of the Colorado system as was Powell. Not only the trunk river, but most of its branches were thus explained. A consequent origin is ascribed to the lateral ravines which descend the structural slopes of the Kaibab arch (*c*, p. 195), but an antecedent origin is announced for nearly all the tributaries of the Colorado; for the San Juan, Little Colorado, and Cataract on the south (*c*, p. 219), and for the San Rafael, Curtis (*b*, p. 63), Fremont (*a*, p. 282), Paria, and Kanab on the north (*c*, p. 188), as well as for the streams that are thought to have once occupied the now dry Summit-valley depressions of the Kaibab (*c*, p. 193), and the House-rock valley between the Kaibab and Paria plateaus (*c*, p. 188).

Replacement of Antecedence by Other Explanations. — The natural history of rivers is to-day better understood than when Powell and

Dutton maintained the antecedent origin of the Colorado drainage system, trunk and branch. It is very probable that these geologists might now modify in some degree the statements that they made thirty and twenty years ago as to the indifference of the streams, especially of the smaller streams, to the displacements of the plateau region. Other origins may be suggested for several of these waterways.

The Smaller Streams of the Grand Canyon District. — Cataract creek (called Cascade river by Newberry, pp. 62, 66, and Coanini creek by Powell, *a*, p. 197) follows in a general way the gentle northward dip of the strata that it dissects, and may well be classified as a consequent stream, revived with every uplift. A possibly consequent origin for that part of Virgin river which passes between the two parts of the Hurricane fault has been suggested above. The Little Colorado follows a monoclinal belt of relatively weak Permian and lower Triassic strata for a hundred miles, and in this part of its course it may be plausibly regarded as a subsequent stream; such was certainly its habit where we crossed it in the Permian belt on the Flagstaff-Tuba road; but for forty miles northwest from this point to its junction with the larger river, it runs obliquely against the gentle structural slope of the Marble platform and enters the main canyon just east of the Kaibab monoclines, a highly significant fact which will be referred to further on. Paria creek has, according to the geological maps of the district (Dutton, *c*, Atlas, sheets II., XXI., XXII.), an anticlinal course in its upper, and a monoclinal course in its lower part. Although the lower part is now deeply incised in resistant Triassic strata on the northeast border of the Paria plateau, its position there may have been gained by headward growth along the once-overlying weak strata of the gently dipping monocline during a lower stand of the land; for the stream seems to be accordant with the strike of the beds. The upper part of the Paria drains the denuded district in which the Kaibab arch fades away to the north (Dutton, *a*, pp. 253, 297); the lateral branches of the stream are here to all appearances normal obsequent streams, whose length increased as the denuded area widened; the trunk stream is merely the axial member of the obsequent group, longer than the laterals because the dip of the strata to the north is gentler than to the east and west. The whole length of the creek may therefore be reasonably explained as an example of spontaneous adjustment of drainage to structure, and not as of antecedent origin. House-rock valley is unquestionably subsequent, as has been implied already on page 124, and as will be more fully considered below. Kanab creek has every appearance of being an obsequent stream, of unusual length, it is true, but associated with receding cliffs of unusual number and strength, in a region of extraordinary denudation. The growth of this creek and its branches, like that of the Paria headwaters, must have been at the expense of many pre-existent consequent streams. The essential principles of the development of such streams were stated by Powell in a general way. He said, speaking of a series of receding cliffs, facing southward: "As the cliffs are undermined, . . . the area with a southern drainage would be increased, the area with a northern drainage correspondingly diminished" (*a*, p. 210). Extensive changes of this kind must have gone on during the great denudation of the plateau cycle, and the growth of long obsequent streams is a natural, almost a necessary accompaniment of the great recession of the cliffs that flank the High plateaus on the south.

The Streams of the San Rafael Swell. — Curtis creek and San Rafael river were not within our field of observation, but they gain importance from having been described as typical antecedent streams by Dutton, who thus explained them because they run across the San Rafael swell without regard to its structure (*b*, p. 63). They may, however, be equally well regarded as superposed through overlying Tertiary strata which may have once covered the denuded swell unconformably. They would thus be associated with a part of Fremont river — called Dirty devil river by Powell (*a*, p. 67), and Gilbert (*a*, p. 130, Plate I.), — which Dutton explains as having been superposed on the mesozoic strata of the Waterpocket flexure (*a*, p. 288), although regarding it as antecedent in its original course on the Eocene (*a*, p. 282). It has already been pointed out that the swell and the flexure are neighboring structures, involving the same series of strata. Dutton demonstrates that the flexure is of pre-Tertiary date (*a*, p. 288, *c*, p. 215), and Gilbert comes to the same conclusion (*c*, pp. 10–12); for Cretaceous strata are involved, and their bevelled surface is unconformably covered by the horizontal Eocene. It is eminently possible, as has already been suggested, that the swell is of the same date, and that its truncated uplift was buried by the Tertiary strata, which certainly once stretched over it. Either superposition or antecedence would locate the two streams on the swell without regard to its structure; but of these two processes the latter seems to me much the less probable for the reason that, if the whole series of strata had been domed, and if the antecedent streams had had to cut down through the successive alternations of strong and weak strata from Tertiary to Carboniferous, a greater amount of adjustment to weak structures than is now seen would have been almost inevitable. This opinion is fortified when it is noted that the two streams in question are of moderate size, and still more when it is seen that they head to the northwest against the retreating Tertiary escarpment, thus suggesting that they are now longer and larger than they were formerly. Their antecedent origin seems improbable, to say the least.

The Summit Valleys of the Kaibab. — The irregular longitudinal depressions, including Summit valley and De Motte park, in the highlands of the Kaibab plateau, have been regarded as of especially obscure origin. Dutton thought them all as the work of a single south-flowing antecedent stream whose waters had been withdrawn in the change from the moist Miocene to the dry Pliocene climate, and whose bed had been deformed by the local uplift of the Kaibab (*c*, pp. 193–195). This view seems open to question because of certain improbabilities that it involves and of certain possibilities that it omits. The association of the Summit valley depression with the axis of the Kaibab uplift, a broad flat arch, with stronger flexure on the east than on the west, seems too close to be the work of chance, — as would necessarily be the case if the depression were the work of a stream whose origin antedated the uplift. The axial line of the longitudinal depression does not now descend continuously towards the canyon; a long northern stretch (Summit valley proper) slopes northward and discharges to the east into House-rock valley and thence to Paria river; a more southern portion (De Motte park) also slopes northward, and, except for shallow sinks on its floor, discharges eastward by a deep ravine down the east Kaibab monoclines. Two other shorter portions also slope northward. Certain intermediate parts slope southward, but they are much shorter than the parts just mentioned. Dutton concludes that all these parts once had a continuous southward slope, and that the present discontinuity of slope is due to a reversal of grade by the uplift of the Kaibab.

The continuous southward slope assumed for the depression seems open to question, especially when it is remembered that the recession of the Triassic cliffs demands a more remote date for the Kaibab arch than early Pliocene. The retreat of the heavy Triassic strata around the north end of the Kaibab suggests that at least some of the mesozoic strata once stretched partly over the uplifted area: they may indeed have stretched all over the Kaibab when the uplift was formed, as suggested by Walcott on account of the absence of fractures in the east

Kaibab flexure, as has already been indicated. If so, there should have been a time in the denudation of the uplifted strata when their lateral slopes were deeply gashed by consequent streams; and when subsequent longitudinal branches of these streams were developed in anticlinal valleys, opened north and south from the head of each consequent stream on the weak Permian and lower Triassic beds that were discovered along the axis of the uplift. The longitudinal valleys would be then enclosed by the retreating escarpments of the Triassic sandstones on the east and west; the Jura mountains of to-day offer many examples of this kind. In the early stages of this development there would be many separate anticlinal valleys along the axis of the uplift, each drained by its own outflowing consequent stream; but as time went on, the branches of the deeper-cut consequents would capture the anticlinal drainage area of the shallower-cut consequents, and as the axis of the uplift descends to the north, these captures would generally be made in a southward direction; thus the drainage areas of the successful consequents would become unsymmetrical; each one would receive a longer anticlinal branch from the south than from the north. As between east and west flowing consequents, the former would generally be more successful than the latter, because the eastern slope of the Kaibab descends to a much lower level than the western; the difference of altitude of corresponding strata in the Kanab plateau and the Marble platform being nearly two thousand feet (Dutton, *c*, Plate II.). If the rule regarding the earlier date of flexures than of faults prevailed here as well as elsewhere, the eastern descent from the Kaibab during the pre-faulting period would have been three thousand feet or more in excess of the western descent; and all the anticlinal valleys would thus come to discharge eastward from near their northern ends, as in Figure 12.

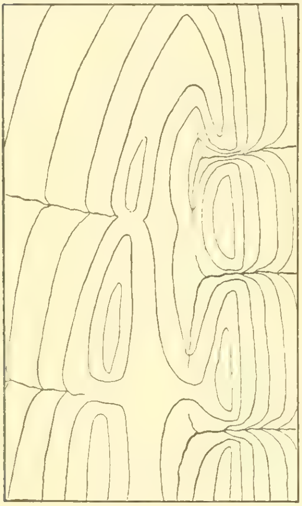

FIGURE 12.
Diagram of self-adjusted drainage on the Kaibab.

The more important of the longitudinal streams thus established on the Kaibab might have worn down their channels into the resistant Aubrey strata before the Triassic sandstones had retreated so far on the east and west as to allow their infacing escarpments to shed water into the lateral subsequent valleys opened on weak monoclinal strata along the flanks of the uplift. But when a sufficient retreat of the Trias had been accomplished and the lateral subsequents had been developed, the axial or anticlinal streams would be reduced to small volume; for much of the drainage of the uplift that used to enter them will at this later stage flow away from them down the stripped structural slopes on either side. The drainage of the stripped slopes forms a new series of lateral waterways; they are not strictly consequent streams which have persisted since the Kaibab was uplifted, but are regenerated successors of the original consequents. It may be noted that the valleys of such regenerated consequent streams will have been eroded first in their upper parts and afterwards in their lower parts, thus reversing the usual order of progress in which erosion acts in a more retrogressive fashion.

The topographical maps of the Kaibab (Dutton, *c*, Atlas, sheets XXI., XXII.) allow us to compare these deduced conditions with the facts. The lateral subsequent valleys have now shifted to the lower ground bordering the Kaibab, by reason of the far and wide retreat of the Trias; the most representative example being House-rock valley, well enclosed by the Trias of the Paria plateau which still stands near the Kaibab on account of the relatively low level of the Marble platform. The regenerated consequents have scored the flanks of the plateau with deep ravines. Four axial valleys all discharge eastward from near their northern ends. Near the northern termination of the Kaibab Carboniferous area, there is a canyon that cuts directly across the uplift, draining a portion of the western Permian monoclinal valley to the corresponding eastern monoclinal valley (House-rock valley) at Adairville; this probably being an example of structural superposition, that is, of a stream whose course was determined when the weak overlying Permian strata still covered the area during the plateau cycle and whose course has been maintained through the resistant Carboniferous strata. The only exception to the rule of eastern discharge is in the case of the southern end of De Motte valley; but this lies beyond the area of greatest altitude on the Kaibab (nine thousand feet) and discharges, as might have been expected, southward to the canyon. It is therefore not necessary to conclude that the "Summit valley" depressions of the Kaibab were ever drained by a single antecedent stream, and it seems advisable to regard the Kaibab uplift as having taken place long before the mesozoic strata were stripped from its crown; thus the evidence from drainage confirms that derived from structure and erosion.

THE ORIGIN OF THE COLORADO IN THE GRAND CANYON DISTRICT. — In view of the various origins other than antecedent that may be ascribed to the branches of the Colorado in the Grand canyon district, it does not seem legitimate to adduce these streams in support of the antecedent origin of the trunk river. That question must be settled by itself, and it is by no means free from difficulty. The antecedent origin of Green river in its passage through the Uinta mountains has been seriously impugned by Emmons (1877), who maintains that it is a superposed river (*a*, pp. 194, 205; *b*). The antecedent origin of certain parts of the Colorado in the Grand canyon district has later been questioned by Jefferson (1897), who points out the southward bends of the river around the Kaibab and Shivwits plateaus, and suggests that these deflections may be consequent on local uplifts instead of regardless of them. To these doubts must be added a whole series of considerations which had no place in the discussions of Powell and Dutton regarding the spontaneous rearrangement of watercourses during the dissection of a region which has suffered repeated movements and heavy denudation. It is true that, as the Colorado runs for the most part on nearly horizontal strata and in a general way transverse to the displacements that its basin has suffered, it cannot be classed with subsequent rivers, for they always follow the strike of a weak stratum in a series of tilted rocks. But the studies of Hayes and Campbell on the migration of certain divides in a region of nearly horizontal strata that has repeatedly suffered slight tilting during the development of its rivers deserve serious consideration in the plateau province, where they have as yet found no exponent. Until this new aspect of the problem shall have been discussed by some one who has a wide acquaintance with the region, it does not seem safe to regard even the trenchant Colorado in its course through the Grand canyon as a purely antecedent river.

In the mean time I cannot resist the temptation of speculating somewhat freely as to the possible development of the great river across the Grand canyon district, especially in view of what has been said in previous sections as to the successive movements that the region has suffered, and in view of the many ways in which drainage lines may be modified during and after such movements. Certain considerations that I wish to bring forward in this connection concern not only the Grand canyon district, but also the adjacent district of the High plateaus and the province of the Basin ranges (or the Great basin) which have not come especially under my observation. In referring to these areas under the names of the Grand canyon district, the High plateau district (these two together making a large part of the Plateau province), and the Great basin province, it must be understood that the existing topographical features are of relatively modern origin, that altogether different topographies prevailed in earlier periods, and hence that the names here used will serve chiefly to designate areas and not forms. The Great basin province was for a time a lofty mountain region; the Grand canyon district was a district of broad plateaus; and the High plateaus were part of a great interior basin. Most of the statements concerning these districts are, it is believed, well assured, but some of them are open to the serious criticism of departing from the conclusions reached by the original observers whose observations are quoted. This section as a whole must therefore be largely speculative; yet the speculations have some recommendation, in that they do not contradict recorded observations, and that they combine to form a mutually consistent scheme of geological events. These speculations may at least serve as targets toward which discussion may be aimed, even if they do not present any ultimate truth.

The Geological History of the Region. — The Basin range province has been disturbed by post-Jurassic plication and by late Tertiary faulting. King wrote that the Great basin "was a region of enormous and complicated folds, riven in later time by a vast series of vertical displacements. . . . The Great basin . . . has suffered two different types of dynamic action: one, in which the chief factor evidently was tangential compression, which resulted in contraction and plication, presumably in post-Jurassic time; the other of strictly vertical action, presumably within the Tertiary" (pp. 735, 744). Dutton makes a similar statement: "These [Basin range] flexures are not . . . associated with the building of the existing mountains. . . . The flexures are in the main older than the mountains, and the mountains were blocked out by faults from a platform which had been plicated long before, and after the inequalities due to such pre-existing flexures had been nearly obliterated by erosion" (*a*, p. 47). Several passages in Gilbert's first western report are of interest in this connection. He concluded "that the Plateau [region] is not a unit in history and origin, and that the only criterion by which it can be distinguished from the [Basin] range country, is the . . . superficial one of table and ridge. . . . The whole phenomena [of displacement] belong to one great system of mountain formation, of which the ranges exemplify advanced, and the plateau faults the initial, stages." He goes on to say that the Basin range province was disturbed at the close of the Jurassic and of the Eocene periods; while the faults in the plateau province are of Tertiary date. In the border land between the two provinces, the later disturbances not merely run parallel to the Jurassic upheavals, but in places actually coincide with them (*a*, pp. 58, 59, 61).

The Effect of the Flexures. — During the earlier elevation and denudation of the Basin ranges, in post-Jurassic times, much waste seems to have been carried from them towards the east and northeast. While the Cretaceous strata of Utah and Arizona are marine deposits, the Tertiaries are continental; and from this it may be inferred that the movements of the Cretaceous-Tertiary interval (such as the Water-pocket flexure) formed enclosed basins, from which the sea was excluded, and into which the waste was gathered as lacustrine or fluviatile deposits. The great volume of the successive Tertiary formations implies that the highlands of the southwest long maintained a considerable altitude. It is possible that their height was intermittently renewed by movements which gave rise, in the Grand canyon district, to the monoclinal flexures; for these flexures had, as has been shown, prevailingly an uplift on the west or southwest. It is postulated that the initial effect of a series of flexures would be to form a flight of very broad steps, such as certainly must have been the case with two well-defined members of the series, the east Kaibab and the Echo flexures; but as the surface of each "tread" may have departed from a level attitude, it is not safe to assert that the height of the top of the flight (southwest) above the bottom (northeast) was equal to the sum of all the "rises." It is, however, here assumed that the top was higher than the bottom, and that the flexures were effective re-enforcements of the mountain-making upheavals in maintaining the Basin range province at such an altitude that it could shed waste abundantly to the northeast. In this connection, it should be noted that the Aubrey cliffs on the south of the plateaus are determined by a north (northeast?) dipping flexure (Gilbert, *a*, p. 46, section), and that the east-dipping strata which are now found close along the fault lines by which the Basin ranges are separated from the plateaus, show some of the strongest dips of the region.

Through all the time during which the mountains of the Basin range province stood higher than the plateau area, the lines of river-flow may be assumed to have followed the direction in which the mountain waste was so abundantly transported; namely, east and northeast; and through the second chapter of this time, after the later flexures had been formed (the inter-flexure-and-fault cycle), the destructive processes which had previously denuded only the mountains of the Basin range province are believed to have extended to the Grand canyon district also; but deposition still continued in the northeast, interrupted only by minor unconformities. The northward retreat of the great escarpments by which the High plateaus are now bordered on the south, must have then begun; the retreat was probably greater on the southwest, where the stepping flexures are supposed to have caused the greatest renewals of uplift. At the close of the cycle that began with flexing and ended with faulting, the Triassic escarpment, for example, may have receded to a line that is roughly marked by three points: the lava mesa on the Shivwits plateau, the junction of the Great and the Little Colorados, and the eastern side of the lava fields around Mt. San Francisco; but something of a northward bend must be made in this line as it crosses the flat arch of the Kaibab. The amount of denudation accomplished during this cycle is indeterminable; yet if any are disposed to limit it to a small measure, their attention should be called to the local instances of great erosion in the Cretaceous-Tertiary interval, when the Waterpocket flexure was essentially baselevelled. As complete a consumption of the up-flexed blocks in the southwest may have been accomplished before faulting took place, although no unconformities remain there to prove it. But although the denuded southwestern area from which the Trias had been stripped may have been reduced to moderate relief, it need not have been a lowland with altitude but little above sea-level, for its streams discharged into interior continental basins, very probably without outlet, on whose floors the Tertiary sediments were accumulating. Some of these basins may have held lakes, intermittently at least; but the occurrence of mountain ranges for hundreds of miles to windward (west and southwest) must have tended to produce a dry climate in the lower continental area to leeward; many of the basins may have been nearly or quite dry, gathering (as I have elsewhere pointed out (*b*)) fluviatile rather than lacustrine deposits at considerable altitudes above the sea.

The Effect of the Faults. — The faulting of the region is the next important occurrence. The faults have their uplift in nearly all cases on the east; hence the eastern area, from having long served as a seat of deposition, became in turn the seat of extensive denudation. At the same time, the western area was greatly depressed from its long residence at a high mountainous altitude. It is not desired to assert that all the faulting of the Basin ranges occurred at the time when their province was dropped to a less altitude than that of the plateaus by the production of great faults along the boundary of the two provinces; the faulting of the ranges was probably a complicated process, but on the whole it is believed to be associated with the lowering of the Basin range province, rather than with the earlier stage of its general elevation. It may be noted that in the southwest (southeastern California) some of the Basin range blocks have been greatly worn away (Fairbanks, p. 70), while in the northwest (southern Oregon) some of the blocks are as yet very little eroded (Russell, *a*, p. 444). In general, however, the post-faulting erosion of the ranges has produced a mature dissection without altogether destroying the block outlines (Powell, *b*, p. 198; Gilbert, *d*, p. 341). The most recent studies of the ranges by Spurr, reported at a recent meeting of the Geological Society of America, indicate that the faulting has been more complicated and longer continued than had formerly been supposed. In certain cases, streams flow through instead of around the ranges of to-day, from which it may be inferred that at least some of the existing drainage of the province had been established before the range blocks were tilted up.

The drainage consequent on the new topography produced by faulting is assumed to have taken the best course that it could find to the southwest. The chief discharge may have here and there followed pre-existent valleys, but with a reversed direction of flow (see extract from Powell, below). Many short-lived lakes may have been formed by the somewhat adverse eastward tilting that has been supposed to have accompanied the faulting of the blocks; but there does not appear to be any positive proof that the tilting may not have been produced at the earlier time of flexing instead of at the later time of faulting; certainly the strata of the Marble platform dip gently eastward between the east Kaibab and the Echo flexures, and here the dip and the flexures seem to be of the same date. In any case, the drainage of a large area of northeastern country, floored with Cretaceous and Tertiary strata, seems to have been gathered at a favorable point of discharge; namely, near the point where the Kaibab uplift had been greatest, and where the exposure of the weak Permian beds had caused the greatest break in the strong Triassic escarpment by which the interior country was enclosed. Westward from the Kaibab, the escaping drainage presumably followed the lowest line that it could find between the Triassic escarpment on the north and the general ascent of the stripped Carboniferous country to the south. Perhaps in some such manner the Colorado found its way across the Grand canyon district to the broken-down mountains of the Basin range province, and thence southwestward to the sea. The river would thus seem to have been for the most part consequent on the form and slope of the surface at the time of faulting, yet it may have been antecedent to various subordinate movements of the crust here and there; and there is a possibility that it may have been in some greater or less degree developed after the faulting by the retrogressive erosion of west-flowing streams that had been encouraged by a favorable tilting of their courses. McGee has suggested the latter process to explain certain streams in "Papagueria" (Arizona and Sonora), whose growth is thought to have been thus accelerated during a time corresponding to what is here called the canyon cycle (*c*, p. 352), and this process certainly deserves deliberate consideration.

It should be pointed out that a consequent origin for the Colorado is indicated by the following passage in Powell's report on the Uinta mountains: "At last the movements which began at the commencement of Tertiary time succeeded in bringing the whole [Plateau] area not only above the level of the sea, but above the general level of the Basin province itself; so that while the Basin province was drained into the Plateau province in earlier Tertiary time, in late Tertiary time the drainage was reversed, and the streams of the Plateau province found their way to the sea by passing through the Basin province. . . . It is the opinion of Mr. Howell, and I believe also that of Captain Dutton, that this drainage was in some cases reversed along the very channels occupied by the ancient streams which ran from the Basin province into the Plateau lakes" (*b*, p. 35). There is in this quotation much more suggestion of a consequent origin of the Colorado than is elsewhere to be found in the reports of the observers whose names have been so often cited here: nevertheless, the published reports give no indication of the manner in which the denudation of the upflexed area on the southwest may have prepared the way for the production of a southwestward slope when the district was afterwards broken and heaved by faulting.

If there be any truth in the suggestion that the Colorado did not cross the Grand canyon district until after the faulting of the plateau blocks, then it was in the cycle of erosion thus initiated (the post-faulting cycle) that the great denudation was essentially completed, leaving little more than the stripping of weak strata and the canyon-cutting for the canyon cycle. The retreat of the escarpments on the faulted blocks during the last chapter of the great denudation must have been over a considerable distance, for each line of cliffs should have been, before the faults were made, worn back further on the west of a flexure than on the east; while now, in consequence of the faults, the reverse relation has been brought about. The total recession since faulting has therefore probably been decidedly greater than the distance by which the cliffs on the east of a fault-line now stand north of their fellows on the west; and thus an even greater antiquity for the faults is suggested than has been thus far suspected.

The Bends of the Grand Canyon. — There are three peculiar features in the course of the Grand canyon: one is the southward bend around the Kaibab, the second is a northward bend toward the mouth of Kanab creek, and the third is a southward bend around the Shivwits plateau. Jefferson has suggested that the first and third of these bends may be consequent on the form of the surface given by the flexures; but according to the analysis of events here presented, the drainage consequent on the flexures ran to the east and northeast, and the westward course of the Colorado was not assumed until after the flexed plateaus had been greatly denuded, and until the denuded surface had been raised on the east by the block faulting. Something later than the initial slopes of the flexed surface should therefore be found to guide the river, if an antecedent or initially consequent origin is not accepted for it. It has seemed to me that certain details in the flexing of the Kaibab and Coconino plateaus may here be appealed to.

The eastern lobe of the Coconino is a striking feature as seen from the lower plateau on the south (Figure 13) and from the valley of the Little Colorado on the east. The surface of the district at the time of flexure was presumably covered by some of the mesozoic formations. Just before the time of faulting, the Trias may have been pushed back to some such outline as would reveal the Permian in the valleys on the south and west of the Kaibab, and perhaps even some of the Aubrey was laid bare on the highest part of the Kaibab. Up to this time, the drainage hereabouts was eastward down the slopes of the Kaibab and Echo flexures, but many longitudinal subsequent streams must have been developed along the weak lower Triassic and Permian strata west of and underlying the Triassic escarpment that was then retreating eastward towards its present position on the axis of the Echo flexure. Now as the drainage of the interior basins of the northeast was turned southwestward by the upheavals associated with the faulting — long after the close of the Eocene — the most available point for its escape was, as has been stated, near the centre of greatest local upheaval (the Kaibab) where the revelation of weak underlying strata had reduced the level of the Trias by sapping, and had thus produced an amphitheatre, open on the southwest. At the same time, the subsequents under the Triassic escarpment were gathered into a single stream to form the Little Colorado, discharging northward; but this result may have been in part the effect of spontaneous interaction among the streams themselves, after their habit in such cases, and only in part the effect of upheaval at the time of faulting. Once reaching the Kaibab amphitheatre, the new-born river followed southward along the subsequent Permian valley which must have been opened along the east Kaibab flexure, until the slopes of the northeast-dipping flexure that limits the Coconino plateau were encountered. The river then turned northwestward along a trough of weak and low-lying Permian strata that occupied a depression between the two uplifts; and it is notable that the small but sharp flexure which bounded this trough on the south may now be traced through the spurs of Carboniferous strata on the southern canyon wall (Dutton, *c*, p. 185). The flexure comes from the southeast, where it forms the northern border of the eastern lobe of the Coconino plateau; it trends northwest, as if to join the now-faulted flexure at the western base of the Kaibab. We had a good view of it from the southern rim and from the bottom of a side canyon. Thus interpreted, it appears that a part of the true Kaibab uplift lies south of the canyon, where it slopes into what is locally known as "the

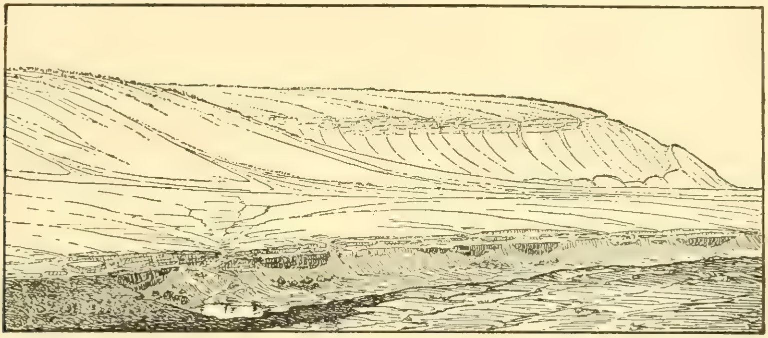

FIGURE 13.

The eastern lobe of the Coconino plateau, as seen from near Lockett's tank. The foreground shows a ravine in the upper Aubrey limestone, once filled with lava, and now partly re-excavated. The "tank" is a waterfall pool. Drawn from rough sketch.

Basin," and ends on reaching the strong flexure by which the strata are turned up into the Coconino; but it is probable that in so far as the terms Kaibab and Coconino have a geographical application, their areas will be separated by the canyon rather than by the flexure that separates their uplifts.

The further northwestward course of the river may have been made inviting if a relative depression or failure of uplift occurred in the eastern Kanab plateau when the west Kaibab faults were formed, and Dutton gives some evidence that this was the case when he describes the northward slope of the Kanab along the southwest border of the Kaibab (*c*, p. 184); but I am at loss to find any conclusive proof of such a condition, apart from the behavior of the river itself. The south bend on the Shivwits may plausibly be explained as a displacement from a once more direct course by reason of the volcanic outpourings which now culminate in Mt. Dellenbaugh.

Speculative Character of the Preceding Sections. — All this is avowedly speculative; and it is presented rather as a combination of various possibilities than as embodying the only permissible explanation for the course of the Colorado. Other stages of the great denudation, now unsuspected, may yet be discovered in the development of the Grand canyon district; new processes of river development, as imperfectly known to-day as was the growth of subsequent streams at the time of the earlier exploration of the canyon, may be added to the growing resources of physiographic study; and all of these elaborate stages and processes will deserve as careful consideration as has been given to the simpler conception of the antecedent river, marked out by the deeper lines of the Eocene lake floor, and remaining unaltered, save for deepening, ever since the ancient lake became dry land.

Nothing less than extended studies over a large area of the Cordilleran region will suffice to determine what value should be given to the various possibilities thus suggested. It is not my intention to discount such studies by attempting to announce their result at once; but only to emphasize the opinion that the facts now on record, combined with such knowledge of the region as our party was able to gather last summer, warrant the consideration of at least one hypothesis alternative to the theory of antecedence, as an explanation for the origin of the drainage lines in the Grand canyon district. I do not on the one hand consider the antecedent origin of the Colorado disproved, but, on the other hand, such an origin does not seem compulsory. The chief objection to the theory of antecedence is not that rivers cannot saw their way through rising mountains, for there are some well-attested examples of such a process, in which its successive steps are more or less fully traced; but rather that this theory makes a single stride from the beginning to the end of a long and complicated series of movements and erosions, overlooking all the opportunities for drainage modifications on the way. The simplicity of the theory is certainly attractive in comparison with the rather tedious length of the considerations that are involved in the attempt to analyze the processes of spontaneous river adjustments; but it should now be generally recognized that nothing less than a deliberate analysis of all movements (of which the uplift of the present plateaus is the last) and erosions (of which the cutting of the Grand canyon is the least) will suffice to discover the actual origin of the Colorado. The preceding paragraphs are offered as the beginnings of such an analysis.

The Erosion of the Grand Canyon.

The Canyon Cycle. — The general uplift that introduced the canyon cycle in the Grand canyon district seems to have been accompanied by a strong renewal of movement on the faults that divide the Basin range province from the plateaus. The northward increase in the heave of the bounding faults between the Basin range province and the plateaus suggests that the uplift of the High plateaus at this time was greater than that of the Grand canyon district. Dutton says: "Until near the close of the Pliocene the High plateaus were not only the theatre of an extended vulcanism, but those portions which never were sheeted over by lavas were low-lying areas, where alluvial strata tended to accumulate. They remained, in fact, base levels of erosion during the greater part of Tertiary time" (*a*, p. 23). It is possible that some movement was renewed on other than the bounding fault-lines at the time of the general uplift, but it has been pointed out above that there is good reason for thinking such movement to have been insignificant on the fault line near Pipe spring. Still, in the south Toroweap valley (Dutton, *c*, p. 94), in the Great Basin (Gilbert, *d*, p. 341), and in the High plateaus (Dutton, *a*, pp. 250, 277), there are various indications of faulting at a much later date than the beginning of the canyon cycle.

Comparison of Glen and Marble Canyons. — Chief among the foregoing considerations that point to the division of the Tertiary history of the Grand canyon district into at least two cycles of erosion is the similar resistance to weathering manifested by the Triassic and the

Carboniferous strata. It would be difficult to determine by ordinary tests which one of these two formations is the more resistant, so strong does each appear; but a very good natural test of their relative strength is found in a comparison of the upper part of Marble canyon, cut in the upper Carboniferous, with Glen canyon, cut in the Triassic rocks themselves, where they descend to the level of the lower plateaus east of the Paria-Echo monocline. The two canyons are of similar date, for the monoclinal flexure that separates them is much older than either canyon; they are of similar width (Dutton, *c*, Atlas, sheet XXII.); and hence the resistance of their walls must be similar. It is true that the widening of Glen canyon has been retarded by the failure of the river as yet to cut down to the weak blue clays that underlie the heavy red sandstones of the Trias; while the stripping of the Trias from the great area of the plateaus south of the Grand canyon, and the recession of the Vermilion cliffs for fifty miles or more north of the canyon have been greatly aided by the sapping of the underlying clays; but even with this aid it does not seem possible to explain the great denudation of the plateaus in contrast to the narrowness of the canyon by a single cycle of erosion.

Stage of Development of the Canyon. — The day has passed when it was necessary to ask whether the canyon is the work of the river; but in the renewed attention lately given to the relation of trunk and branch valleys, certain features of the canyon serve as important witnesses. In spite of the youth of the canyon, its branch streams generally enter at accordant grade with the main river, and thus testify to the promptness with which side valleys are cut down to the depth of the main valley at their points of junction. This feature must be considered in some detail.

Rapids in the Canyon. — The canyon is so young that the great river at its bottom has not yet established a completely graded channel. True, there are no leaping waterfalls now remaining: "Throughout the cañons there are no cataracts; that is to say, at no place does the river fall from a ledge of rock into the pool below" (Gilbert, *a*, p. 75). But there are still many rapids, especially in those parts of the canyon where the fundamental crystallines are trenched. When these resistant ledges are rasped away, the upper canyon will be significantly deeper than it is now. On the other hand, the corrasion of the canyon must at present be proceeding at a slower rate than at some earlier time, before the development of the graded stretches that now constitute the greatest part of the river. It was the existence of these graded stretches, where the river is hardly more than a transporting and comminuting agent, that brought Powell's boat journey within the limits of possibility, even while the lingering rapids made it terribly dangerous. The occurrence of rapids on the down-stream side of boulder heaps that have been washed into the main canyon by the flooded streams of side chasms, also indicates a retarded rate of corrasion by the main river. Powell mentions several such obstructions (*a*, pp. 82, 83, 97); Gilbert gives a more explicit account of them and points out their probably temporary character. He says that many of the tributary canyons "are of very rapid fall, and are occasionally traversed by powerful torrents, which sweep down bowlders of great size — in some instances 10 or 15 feet in diameter — and heap them in the main cañon in dams, that must often be of great depth. Over each of these the water finds passage at the edge opposite the tributary, and descends the lower slope with swift current and broken surface; and thus arise the great majority of the rapids." It is further pointed out that there are times "when each of these dams in turn is removed . . . so that, while the dams will recur at the same localities and with the same characters, they cannot be regarded as strictly permanent" (*a*, p. 71; see also Dutton, *c*, p. 241).

It may therefore be concluded that although the canyon is still to be deepened, the river as a whole approaches and for considerable parts of its course actually reaches the delicate balance between degradation and aggradation which characterizes a maturely graded stream. After such a condition is reached, further deepening of a valley is possible only with the decrease of the load furnished to the main stream by its side streams, in the later maturity of the region.

Junction of Trunk and Branch Streams. — It is now to be determined how the side streams join the main river at this relatively early stage in the present cycle of the Colorado. The importance of this question turns on the prevailingly discordant junction of side and main valleys in strongly glaciated mountains, as has recently been pointed out by De Lapparent and Richter for the fiords of Norway, by Gannett for Lake Chelan in the Cascade range, and by Penck for the valleys of the Alps. I have lately prepared a general review of this problem in connection with my own observations on the valley of the Ticino in southern Switzerland and elsewhere in Europe (*c*, p. 310; *d*, p. 138). It has been contended by some that the discordant junction of side and main valleys in the Alps is the normal result of the more rapid deepening of the main valley by its larger stream, even to the point of thus accounting for lateral valleys standing five hundred or more feet over main valleys whose flood plains are ten or twenty times as broad as their rivers. On the other hand, the observers above named conclude that the discordance is due to glacial erosion. If the former view were correct, then surely the discordance of side and main valleys ought to be very strong in the Grand canyon, where there is no question of glacial erosion, where the disparity of volume between trunk river and side streams is notoriously great, and where the main valley is still so young that no significant widening of its floor has been yet accomplished. Yet singularly enough, the side canyons of the Colorado join the main canyon at accordant levels in nearly all cases. The views from the southern rim of the canyon at various points near Hance's and Cameron and Berry's, and still better from the great Red-wall spur that advances northward from the "copper mine" on the Grand view trail, show repeated instances of dry or nearly dry lateral canyons, only five or six miles long, which are nevertheless cut down at their mouths as deep as the main river, if their lower course lies on the stratified rocks. It is only where the main canyon narrows on entering the resistant crystallines that the side canyons are held up at a discordant level; and even there the large lateral canyons seem to enter closely at grade (see detailed map, by Bodfish, Dutton, *c*, p. 258, Plate XLII.). However discordant the side and the main canyons may have been during a still earlier stage of the present cycle of erosion, Playfair's law is already exemplified to-day; and if, under conditions of peculiar difficulty, some of the smaller streams have not yet reached a normal relation to the master stream, they only prove the verity of the law by the need of their being excepted from it.

As my own views of the canyon were only in the middle of the Kaibab section and from Vulcan's throne in the Toroweap, the following references to records made by others may prove pertinent in this connection. Powell describes his ascent of a side canyon west of the Kaibab, and mentions waterfalls in its course, one of which was one hundred and fifty feet high; but as no fall is mentioned at the mouth of the side canyon, it probably unites with its master in accordant fashion (*a*, p. 92). A little further down the main canyon, a stream from the north leaps into the river "by a direct fall of more than a hundred feet" over a "bed of very hard rock, . . . thirty or forty feet in thickness" (*a*, p. 93). Before reaching the crystallines of the Shivwits canyon, "a little stream, with a narrow flood plain, comes down through a side cañon" from the north. An Indian settlement was found there, with fields of corn and squash (*a*, p. 96). Even within the crystallines of the Shivwits block, small side streams of "gentle slope" are reported by Wheeler as entering the main river and forming boulder rapids, but no mention is made of falls at the stream mouths (pp. 166, 167). Plate XVII., in Dutton's Monograph, reproduced from a photograph, shows two side canyons entering the narrow inner gorge of the main canyon just east of the Toroweap, and joining the main river in accordant fashion. Evidently, then, hanging valleys have no important place in the Grand canyon; and the hanging lateral valleys of the Alps, whose floors are five hundred feet or more above the open flood plains of their main valleys cannot be explained by normal river erosion.

Some striking examples of hanging valleys in a very narrow canyon are, however, described by Gilbert in the case of the North fork of Virgin river in southern Utah, where it cuts through the massive Triassic sandstones. This narrow defile is many times deeper than broad; its walls are nearly vertical and parallel for the greater part of their height, but they depart sufficiently from the vertical, now to this side, now to that, to hide the sky from the adventurous observer who follows the narrow, boulder-strewn stream bed. "The side cañons all partake of the character of the main, but, being worn by smaller streams, are narrower, and their bottoms are of steeper grade. Many of them at their mouths are not cut so deep as the one we followed, and discharge at various heights above the river" (*a*, p. 79). Gilbert's figure of this canyon has become well known from being copied on the binding of Leconte's "Elements of Geology," as if in witness of the efficiency of erosive processes; but it may be noted that a plain of denudation, truncating the edges of upturned strata, is a much more impressive though less outspoken witness to this conclusion.

THE GEOLOGICAL SECTION IN THE CANYON WALL. — The excavation of the Grand canyon is properly regarded as a colossal work. Standing on the southern rim, the view of the chasm is overwhelming; yet the prospect includes four other records of erosion, and suggests two more still, in comparison with any one of which the excavation of the canyon is but a small matter. This has all been pointed out by Powell and others; but it deserves repeated statement.

The geological section exposed in the northern side of the canyon in the Kaibab, as seen from any of the promontories in the neighborhood of Cameron and Berry's or Hance's hotels, includes the fundamental crystallines, the inclined strata of the Grand canyon series (Algonkian), twelve thousand feet thick, and the palæozoic series, over four thousand feet thick.

The strata of the Grand canyon series are seen in the form of a wedge with its apex pointing westward, as in Figure 14; its lower members rest unconformably on an inclined floor of denuded schists, while the basal members of the palæozoic series rest unconformably on a horizontal floor denuded on the schists continuously with the bevelled upper surface of the wedge of the Grand canyon series.[1] The skyline of the Kaibab is, as has been pointed out above, the edge of a stripped struc-

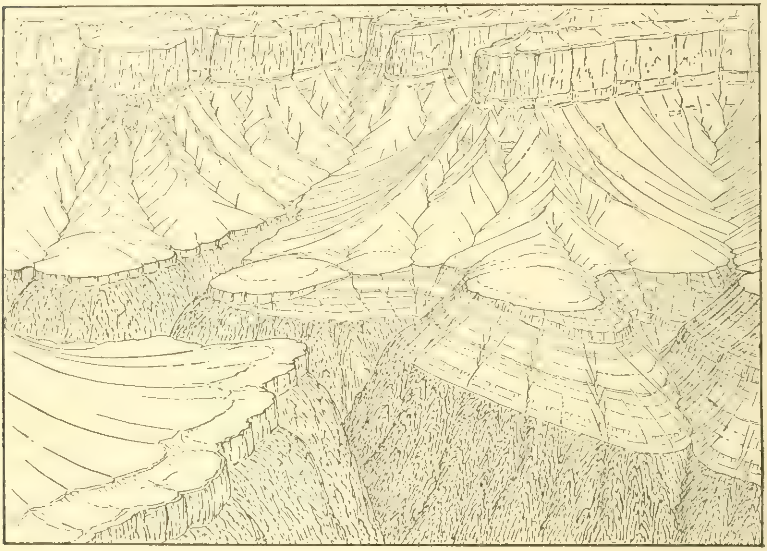

Figure 14.

The Algonkian "wedge" between the crystalline foundation and the palæozoic series; looking north across the canyon from near Hance's on the Coconino river. Constructed from rough sketch.

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[1] The view of this structure given by Powell (*a*, p. 212, Figure 79) is somewhat misleading, for it represents the inclined members of the Grand canyon series with a horizontal base, as if they were examples of cross bedding on a gigantic scale. The correct relation is shown in figures by Walcott (*b*, p. 551; *e*, p. 507 — this from a drawing by Gilbert — and *c*, p. 553) and by Frech (p. 477). It may be noted that a sheet of basalt or diabase, which occurs near the base of the Unkar series and which has been regarded as contemporaneously interbedded by Walcott (*e*, p. 508) and doubtfully described as either an intrusion or a surface flow by Frech (p. 477), seemed to us to be an intrusive sheet or sill, because it appeared to step from one bedding plane to another by distances of a score of feet or more at one or two places; but this opinion is based only on field-glass observation at a distance of over a mile.

tural plain, from which more than six thousand feet of strata have been removed. There have, then, been two periods of essentially completed erosion, marked by the floor of the Grand canyon series and by the floor of the palæozoic series, and one period of far advanced erosion, marked by the skyline of the Kaibab; and three alternate periods of enormous erosion elsewhere to supply the strata locally deposited in the Grand canyon series, the palæozoic series, and the mesozoic series; and the work done in any one of these six periods far outranks that thus far accomplished in the erosion of the canyon. Excepting the periods of mesozoic deposition and erosion, all this history is recorded in the canyon with the clearness that one ordinarily sees only in colored diagrams on a blackboard, and with infinitely greater detail and impressiveness.

The Two Unconformities. — The double unconformity associated with the "wedge" of the Grand canyon series (Figure 14) deserves special attention. The floor on which these strata rest is of remarkable evenness, in spite of the great deformation of the fundamental schists. It is exposed in the section on the northern wall of the canyon for the greater part of a mile, dipping under the river at the lower (eastern) end and terminated at its upper (western) end by the surface of the second unconformity. The line here seen may be taken as a fair sample of a large area of the floor on which the Grand canyon series rests, because it is exposed by the chance section made by the river, whose course was originally selected with no regard whatever for the then deeply buried crystalline foundation of the region. The whole surface must have been much larger than the part seen in the canyon; for if the crystallines were evenly truncated here, they must have been similarly worn down over a large extent of adjoining territory; and, moreover, a formation that measures ten thousand feet in thickness, like the Grand canyon series, cannot be of merely local development. The conclusion seems compulsory that before the deposition of the Unkar strata (the lower members of the Grand canyon series, Walcott, *e*, p. 506) the crystalline rocks were reduced to a plain of admirable evenness, either by marine or by subaerial forces; and however many cycles or partial cycles of erosion were devoted to this ancient task, the last cycle must have been undisturbed until it was very far advanced.

The floor on which the palæozoic strata lie was formed by extensive erosion after the tilting of the crystalline schists with their heavy cover of the Grand canyon series, the compound mass being planed down to an almost even surface. The Kaibab section of this floor is over fifty miles in length along one side of the river, or about forty miles in a direct line. Through very nearly all this distance, the floor is covered by the basal (Tonto) sandstones of the palæozoic series. When the actual contact is seen, it is found to be ragged, but in the twenty-mile stretch that I saw, the vertical inequalities of the floor were trifling in comparison to its horizontal extent. A few miles west of the Grand view trail into the canyon, a broad flat mound of the crystallines rose high enough in the northern wall of the canyon to interrupt the whole thickness of the Tonto sandstones (Figure 15), but this was the only significant unevenness of the surface between the Tonto and the schists visible in that direction. A short distance east of the apex of the "wedge," the more resistant members of the older series are not so well planed down as are the crystallines just west of the same point, and the Tonto sandstone is there greatly reduced in thickness or altogether wanting for large fractions of a mile. But these inequalities in the

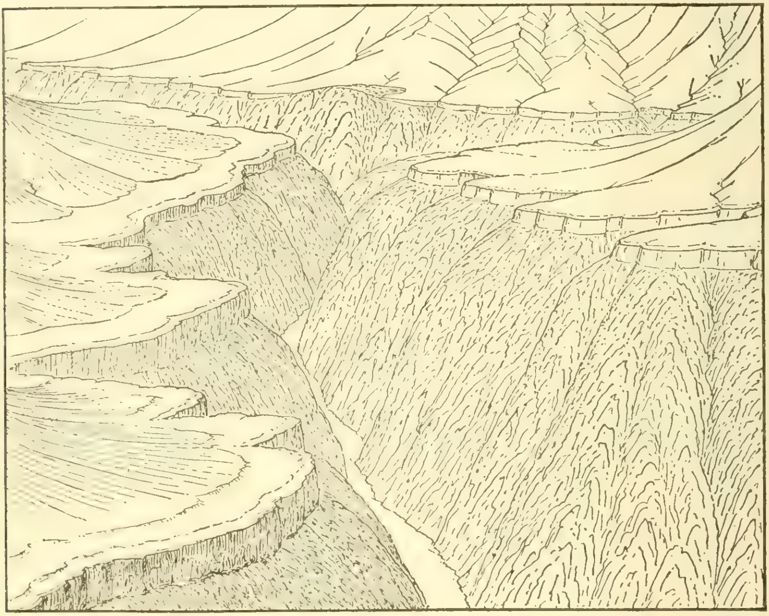

FIGURE 15.

The canyon in the crystallines, looking down the river (northwest) from Coppermine spur, Grand View trail. The crystalline floor is generally covered by the Tonto sandstone; but a low crystalline monadnock rises through the Tonto in the distance. Drawn from a sketch.

palæozoic floor are of small value compared to the strong relief that must have been developed in the mature stage of erosion on the tilted Grand canyon series and their underlying schists. The ancient floor was certainly a topographically old surface, in a far advanced stage of its erosion cycle.

The extension of the palæozoic floor further west may be briefly sketched. Powell noted "patches of granite, like hills thrust up into the limestone" in his passage through the Kanab section of the canyon (*a*, p. 92). Dutton describes the floor in detail, emphasizing its small relief, and Holmes made an admirable drawing of the southern wall in the Kaibab section of the canyon (*c*, pp. 178–181, 207, 209, Plate XXXV.). Newberry wrote, when describing the section in the Shivwits plateau: "The erosion of the cañon has beautifully displayed the ancient surface of the granite, and shows it to have been extremely irregular; hills several hundred feet high, many of which have precipitous sides, and deserve the name of pinnacles, have been exhumed from the sediments in which they were enveloped. The sandstones and shales are seen to have been deposited quietly around them; their strata, nearly horizontal, abutting against their sides" (p. 58). Gilbert says that "all along the southwestern border of the plateau region in Arizona, the Archæan schists and granites are seen beneath nonconforming members of the Grand cañon rock system; usually the Tonto sandstone" (*a*, p. 186), and his diagrams represent the contact of the two systems by a straight line. My lamented classmate, Marvine, records similar observations (p. 199). A photograph of a point in the western part of the Grand canyon, near Peach spring, Ariz. (View No. 173, taken by W. H. Jackson and Co., Denver, Colo.), shows the crystallines as evenly capped by the Tonto as they are in the Kaibab section. The palæozoic floor is thus traced for over a hundred miles from the Kaibab section, and in spite of its inequalities, it is nearly everywhere capped by the lower palæozoic strata. It was certainly a surface of moderate or small relief.

The slope by which the crystallines descend to the river under the stratified rocks has different profiles east and west of the apex of the "wedge." Under the Unkar, the slope is uniformly steep from top to bottom. Under the Tonto, a bench of crystallines stands forth for several hundred feet, and then bends by a strong curve to a slope as steep as that beneath the Unkar (Figures 14 and 15). The persistence of this feature in the view down the river from a point over the edge of the "wedge" is remarkable, and strongly suggests that the crystallines under the Tonto are weaker in their upper than in their lower portion. It occurred to me that this might be the result of deep weathering of a pre-Tonto peneplain, before it was buried by the palæozoic series, and that the incursion of the Tonto sea over the peneplain was too rapid to allow the waves to abrade anything more than the superficial soils; thus leaving the weakened rocks to reveal their weakness in the canyon profile to-day. The sub-Unkar floor, on the other hand, seems to have been smoothly worn down to firm rock by marine abrasion before it was covered by Unkar sediments; but whether the advancing Unkar sea destroyed great mountains of schists or merely planed off the soils and weathered rocks of a pre-Unkar peneplain is an unsolved question.

CORRELATION OF WATER STREAMS AND WASTE STREAMS. — The palæozoic walls of the canyon in the Kaibab exhibit a combination of cliffs, slopes, and platforms in great variety, appropriate to the horizontal structures on which they are eroded. The widening of the canyon here has not yet produced broad benches or platforms, although a systematic beginning of their development is repeatedly observed; but in the Kanab, Uinkaret, and Shivwits sections of the canyon the upper surface of the Red-wall group has been denuded to form a broad platform, called the esplanade by Dutton, to which fuller reference will be made below. Returning to the Kaibab, a pleasing comparison may be made between the path of a running stream of water along the valley bottom and that of a creeping stream of waste down the valley side; the simplest examples for comparison being in horizontal strata such as are so magnificently displayed in the canyon walls. In both cases, graded slopes are first established in discontinuous stretches on the less resistant strata, while cliffs remain ungraded on the outcrops of the stronger strata. The close analogy of the two cases is brought to mind by comparing a plunging fall of water, leaping down the nearly vertical face of a resistant stratum in the valley bottom, with the discontinuous fall of rock waste over the cliffed outcrop of a resistant stratum on the valley side. The evenly graded reach of the water stream on the weaker strata above the fall corresponds with the flat platform in the valley walls above the cliff; and the "cave-of-the-winds" in the weak strata just behind the waterfall corresponds with the hollow or "rock-house" beneath the overhanging base of the cliff; the scanty heap of rock fragments beneath the waterfall corresponds with the sheet of rock waste (with the coarsest fragments lowest down) that cloaks the under slope of weak strata from the rock-house down to the back or inner margin of the next platform below. It is natural that the proportionate development of the several elements, cliff, rock-house, talus-slope, and platform on the valley side, should vary from that of the corresponding elements, cliff, cave-of-the-winds, rock-heap, and reach along the valley bottom, on account of the difference of behavior between a sluggish stream of waste and a nimble stream of water. In the latter, the vertical element of form is reduced to a small fraction of the horizontal at an early stage of the cycle; while in the former, the vertical dimension remains strong until the stage of maturity is past.

Graded reaches make the greatest part of even a young river, but graded platforms widen slowly on valley sides and attain no great breadth until late maturity. It is along these graded reaches that the finer waste from the rock-heap, as well as from further up-stream, is steadily carried forward; comminution of rock waste is active, but erosion of the rock bed is here extremely slow. Rock-heaps under waterfalls are so unimportant topographically that they are seldom included in geographical descriptions; yet they are really characteristic elements of a young river's course in structures of the kind here considered. Talus slopes on valley sides are of much greater dimensions; so great indeed that they form a systematically graded surface. Their grade is steep compared to that of the platform because their waste is coarse. These accumulations of coarse waste, both rock-heap and talus, consist chiefly of fragments broken from the cliff above; the fine waste that is weathered from them is carried forward or down-stream, while the surface on which they rest retreats backward or up-stream. Rock-heap and cave-of-the-winds vary inversely; the sum of their vertical measure together with that of the face of their fall ledge (a constant) makes the height of the fall: talus-slope and rock-house are similarly related. The cave-of-the-winds is larger but less habitable than the rock-house; but in the wet as well as in the dry cave, air-movement is an important factor of erosion. The cliffs in the two cases are so much alike that they need no further comment.

The strongest fall-and-cliff-makers endure longest, while the less strong ones are sooner worn back until they disappear under a graded reach or platform (Gilbert, *b*, p. 100), or retreat into the cave-of-the-winds or the talus-slope under a master cliff. Among the disappearing falls and cliffs, those which are down-stream from a very resistant ledge will be the first to vanish, because their more rapid recession will soon push them back under the slowly retreating master ledge; the canyon walls give many examples of this kind. On the other hand, the disappearing falls and cliffs will remain in evidence for a much longer time if they are up-stream from the master ledge, for there they must recede until they are concealed beneath the backward extension of the gently sloping graded reach or platform below them. Thus a master ledge promotes the development of a high fall or long talus-slope beneath it, and of a long reach or broad platform above it ; and when this relation is established, the number of separate elements of form in valley bottom or on valley side is much less than it was in earlier youth. The great escarpments of the High plateaus exhibit the concentration of all the large and small cliffs of youth in a relatively small number of great cliffs in late maturity ; and thus still again confirm Dutton's opinion that the erosion of the plateaus and the erosion of the canyon took place in different cycles, separated by a strong uplift of the region.

The general principles here reviewed are of wide application, but in regions of moderate relief and moist climate, the forms of valley sides are seldom analyzed : certainly they are frequently overlooked in geographical descriptions. In the Grand canyon district, where the relief is on a huge scale, and where the arid climate lays bare every topographical detail, the elements of form assumed under moving streams of waste on valley sides are conspicuous ; they are glorified by mere magnitude so that one is tempted to treat them as a new class of topographic forms, until it is recognized that they are only new variations on an old class, examples of which are to be found in all regions of horizontal structure. The canyon walls in the Kaibab and the great mesozoic "terraces" that overlook the plateau from the north exhibit the earlier and later stages of all these forms with great clearness.

Cirques, Cusps, and Niches. — The many variations in the horizontal pattern of the cliffs in the canyon walls have been briefly described by Dutton (*c*, pp. 258, 259). The cliff outline, as seen in plan, has two expressions (Figure 16). In some cases, the re-entrants of a cliff are sweeping concave curves, but little notched, while the intervening salients are sharply attenuated cusps. In other cases, the re-entrants are narrow and acute notches, while the salients are broad and rounded spurs. The difference between these two cases seemed to depend partly on the drainage area of the uplands, whose waters are shed over the cliffs from higher levels, and partly on the amount of erosion that the cliffs have suffered ; these two factors being indirectly connected.

Where an upland sheds a stream over a cliff, the cliff will be cut back much faster by the stream than it will be weathered back on the inter-stream front ; here the re-entrant must be an acute notch ; while the adjoining salients will be spurs with rounded front. But where the upland is of so small an area that it cannot gather streams, then the head of the axial line of a re-entrant has no more importance as a stream way than the lines that join it from either side; as a result the retreat of the walls will be of about uniform value for a considerable length of front, and the head of the re-entrant will here assume a concave or cirque-like pattern. At the same time, the widening of the re-entrant will narrow the adjacent spurs to mere skeletons of their original size and sharpen their salients into cusps.

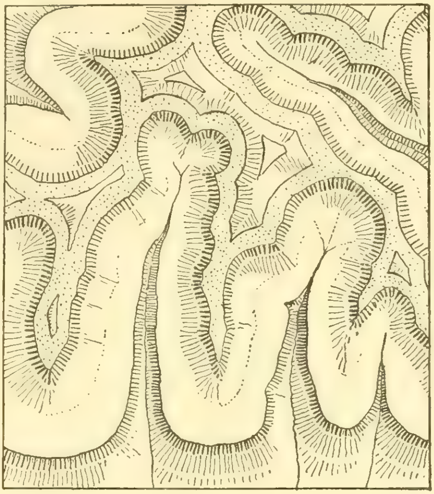

FIGURE 16.

Notches and cusps in cliff patterns. Diagram of two cliff-makers; the lower one showing acute notches between rounded spurs; the upper showing rounded cirques between acute cusps. Slightly modified from Bodfish's map of part of the canyon wall in the Kaibab. (Dutton, *c*, Plate XLII.)

If this analysis be correct, rounded spurs and sharp re-entrant notches should prevail in the cliffs near the base of the canyon walls, because streams will generally descend into such re-entrants from the higher slopes; unless, indeed, time enough has elapsed for the strata overlying a low-level cliff to have been swept away, and the area of its platform reduced by the widening of adjoining side-canyons, so as to imitate conditions that would prevail only at higher levels in an early stage of erosion. On the other hand, cirque-like re-entrants should prevail in the high-level cliffs that rim the sides of the great spurs of the canyon walls, and the spurs between these cirques should be acutely sharpened cusps. Cirque-like curves should occur in the rim of the plateau only where no significant area sheds drainage from it, and notched re-entrants should occur in the high-level cliffs chiefly at the head of side canyons where back-country drainage is delivered to them. As a consequence of all this, a rather systematic relation should frequently be found between the two sets of forms; the curved re-entrants of the higher cliffs should frequently stand back of and above the sharp re-entrant notches of the lower cliffs; while the sharp spurs of the upper cliffs should project forward along the axis of the rounded spurs of the lower cliffs.

As far as this scheme was tested on the ground, it seemed to give reasonable explanation to a good number of examples; but unfortunately it was not reduced to formal statement until after leaving the canyon; hence, as so often happens, the observations made on the ground were less critical than they might have been if they had been immediately accompanied by analysis.

The niches of the massive Red-wall limestone, described but left unexplained by Dutton (*c*, p. 260, Plate XLI.) seem to exemplify a special case of a problem that McGee has discussed in connection with the "origin and hade of normal faults" (*a*, p. 296). The niches all occur over the heads of subordinate ravines or gulches, and are, therefore, to be associated with the sapping by the underlying weaker strata and the falling away of the basal part of the massive limestone. In the absence of numerous planes of bedding and jointing, the upward breaking of the rock may be compared to the upward propagation of a fault; and McGee shows that in such case the fracture must be a curved surface with decreasing hade upwards, so that the broken face may eventually become vertical or even overhanging. The overhanging arch by which the niche is covered seems to correspond to the upper part of such a fracture.

THE ESPLANADE. — Although the Kaibab and the Uinkaret are only forty miles apart, the canyon in these two plateaus exhibits very unlike cross-profiles. In both, the double cliffs of the upper Aubrey are repeated with similar outlines. In the Kaibab, a platform of moderate width is worn on both the Red-wall group and the Tonto sandstone, the lower one being rather wider than the upper, and the two being separated by the huge Red-wall cliff and the long gray waste-covered slope of Tonto shales beneath it. In the Kanab and Uinkaret sections, as seen from Vulcan's throne at the mouth of the Toroweap valley, the Red-wall platform is greatly widened; it becomes a broad floor, stretching far up and down the canyon, and fully deserving the name, esplanade, given by Dutton; but the Tonto platform is wanting; the cliffs from the top of the Red-wall descend with their steepness little diminished nearly to the river, enclosing the narrow inner canyon or chasm; while the Aubrey walls of the upper or outer canyon are five miles or more apart. It is significant that the floor of the esplanade everywhere lies on the same stratum, namely, a calcareous sandstone; the upper member of the Red-wall group.[1]

Two Theories of the Esplanade. — Dutton explained the esplanade as a mature valley, eroded during a pause in the uplift by which the broadly denuded plateaus gained their present altitude. During this pause, "the river sought and quickly found a new base-level at the bottom of the great esplanade of the Grand cañon. . . . The cliffs . . . receded away from the river, gradually developing the broad avenue of the outer chasm. . . . Again the country was hoisted, this time more than before. . . . Swiftly the inner gorge was scoured out, and the chasm assumed its present condition. At present the uplifting force is inactive . . . and the river has nearly but not quite reached another base-level" (*c*, p. 121).

It had been suggested to me before our trip to the canyon that it was not necessary to assume a pause of this kind in the later uplift of the plateaus in order to account for the esplanade, for its relation to the resistant Red-wall group was such as to indicate its dependence on structure rather than on a former baselevel. Several reasons for adopting this view presented themselves.

Comparison of the Kaibab and the Kanab Sections. — In the first place, if the form of the canyon in the Uinkaret, Kanab, and Kaibab plateaus were dependent on recent sub-cycles or episodes of erosion, rather than on structure, some indication of the esplanade ought still to be apparent in the Kaibab section at an altitude corresponding with that so well maintained further west; but inasmuch as the uplifts of the Kaibab are believed to be of much earlier date than the erosion of the canyon, the esplanade ought to stand at a lower geological horizon in the Kaibab than in the Kanab. No trace of an esplanade is, however, to be recognized in the Kaibab; the descent from plateau to river is there accomplished by a general incline, broken only by the benches of the Red-wall and Tonto groups, as stated above. On the other hand, the slopes of the Kaibab walls and the cliffs and esplanade of the Kanab walls are easily explained if they are dependent on local structural conditions; and there is independent evidence that the appropriate conditions actually occur. It is evident that if the Tonto shales that form the slope between the Red-wall and the Tonto cliffs in the Kaibab should become more resistant as they pass westward into the Kanab, their face would steepen, and the Red-wall cliff would come to stand more immediately over the Tonto; at the same time the Red-wall platform would broaden to form the esplanade. Observations are not lacking to support this supposition. Gilbert noted that, at the entrance of Kanab creek into the main river, the Tonto shales are of "firm texture" (*a*, p. 70). Dutton says more explicitly: "In the Kanab division the whole series of nearly 2,500 feet thickness [Red-wall and below] is wonderfully massive, and the partings of the strata are comparatively few. In the Kaibab the great 750-foot limestone is as solid as ever, but most of the other members have become laminated much more minutely than in the Kanab and Uinkaret, and are of more perishable texture" (*c*, p. 257). As these values of resistance are precisely such as would undermine the Red-wall cliff-makers in the Kaibab and support them further west, a structural explanation for the esplanade seems to be sufficient.

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[1] In Gilbert's section of the canyon at the mouth of Kanab creek, a heavy cross-bedded sandstone of the lower Aubrey is placed at the floor of the esplanade, and no such sandstone is shown in the wall of the outer canyon above the esplanade (*a*, p. 70, Figure 38); while the section of the Shivwits canyon sets the floor of the esplanade on the Red-wall group, and places the cross-bedded sandstone of the Aubrey as a cliff in the wall of the outer canyon. Gilbert explains this variation by the statement that the order of the hard and soft beds in the lower Aubrey is not constant (*a*, p. 177); but Dutton says: "The cliff formed out of the upper and lower Aubrey series is very remarkable for the constancy of its profile throughout the entire extent of the great chasm." As far as my own observations went, they agreed with the latter view. It is possible that the cross-bedded sandstone which Gilbert placed on the floor of the esplanade at the entrance of the canyon of Kanab creek into the Grand canyon was really the calcareous sandstones which as a rule forms the upper member of the Red-wall group, capping its great cliff.

Eastward Fading of the Esplanade. — In the second place, if the eastward extension of the esplanade be traced on the topographical maps, it gradually loses definition by decrease in its breadth and by increase in the number of ravines that break its front; and in the easternmost part of the Kanab it can hardly be recognized. This is best seen by tracing the southern side of the canyon, for on approaching the Kaibab, the form of the northern canyon wall is much complicated by the displacements that occur there, and bedded structure has not alone a full control. A gradual change of form of this sort is an appropriate consequence of the structural origin suggested for the esplanade.

Relation of the Inner and Outer Canyons. — In the third place, the position of the inner canyon along the middle of the esplanade is, as was suggested to me several years ago by Mr. C. H. White (then one of my graduate students, now instructor in mining at Harvard), singularly significant of a single period of erosion. This may be understood by considering the two alternatives in order. If the esplanade represented a mature valley floor, broadened by the lateral swinging of the river during a lower stand of the land, rather than by the rapid wasting of the weak lower Aubrey layers in contrast to the persistence of the strong Red-wall group, then when renewed uplift revived the process of canyon cutting, the river must have occupied an irregular path along the esplanade, and the inner canyon would have been cut at one place near the northern wall of the outer canyon, and at another near the southern wall. This condition is actually illustrated in the valley of the Rhine; here a narrow inner gorge is incised in the flat floor (esplanade) of a broad trough which in turn is eroded beneath the bordering uplands; a structural origin for the trough is inadmissible because the rocks are greatly deformed; and, moreover, river gravel and silt still cover the floor of the trough. The narrow gorge is intrenched irregularly along the trough floor, sometimes turning so far to one side that a continuous descent leads from the high upland directly to the river, while a correspondingly broad mid-level floor remains on the other side. The same relation occurs in the valley of the Moselle, whose young gorge meanders conspicuously from side to side in the floor of the mature trough. The valleys of the Lot and the Dordogne in southwestern France exhibit similar features, except that the younger or inner member of the composite valleys are here opened wide enough to have scrolls of incipient flood plain on one or the other side of the river, while flood plains are as yet only just begun in the gorges of the Rhine and the Moselle.

If, on the other hand, both the outer and the inner canyons of the Colorado are the work of a single cycle of erosion, and the esplanade is of structural origin, then it is necessary that the walls of the outer canyon should retreat symmetrically on either side of the inner canyon, and that the inner canyon should bisect the floor of the esplanade thus produced. This case would correspond to that of all one-cycle valleys in horizontal strata, where the symmetry of the benches and slopes on the two walls results from their essentially equal retreat under the weather. Innumerable illustrations of such symmetry may be seen in the side canyons of the Kaibab section, where the Red-wall cliffs are placed symmetrically with respect to the narrow gorges in the Tonto sandstones below and between them; the detailed map of part of the canyon in the Kaibab by Bodfish already referred to (Dutton, *c*, Plate XLII.), gives good illustration of many examples of this kind.

Now returning to the facts, there seems to be little doubt that the inner canyon bisects the esplanade. Its medial position is very striking in the majestic view that we had of both these features eastward from Vulcan's throne; a view made famous by Holmes's wonderfully effective drawing (Dutton, *c*, Atlas, sheet VI.). All the published maps and sections of the district exhibit this arrangement in the most systematic manner through the Kanab and Uinkaret plateaus, and as well in the lateral canyons of Cataract and Kanab creeks as in the main canyon. Even the first accounts of the canyon made mention of the medial course of the inner chasm. Ives, descending from the plateau south of the Kanab section by a branch canyon, reached a floor (a branch of the esplanade) which, when seen from the enclosing cliffs, looked smooth, but which was really covered with hills thirty or forty feet high; "along the centre we were surprised to find an inner cañon, a kind of under cellar" (p. 107). Powell's first mention of the esplanade, as seen from the cliffs near the border of the Kaibab and Kanab plateaus, is as follows: "The walls seem to rise very abruptly, for two thousand five hundred or three thousand feet, and then there is a gently sloping terrace, on each side, for two or three miles, and again we find cliffs, one thousand five hundred or two thousand feet high. From the brink of these the plateau stretches back to the north and south, for a long distance. . . . The effect of the terrace is to give the appearance of a narrow winding valley, with high walls on either side, and a deep, dark, meandering gorge down its middle" (*a*, p. 92; also p. 196). It should be noted, however, that the topographical maps show the Shivwits section of the canyon to have walls of less symmetrical form than prevails further east; but not having seen this part of the canyon, I shall not venture to discuss its complications.

Relation of the Esplanade to the Toroweap Fault. — Finally, it may be noted that the early date given on page 146 for the Toroweap-Sevier fault is not at all inconsistent with the discontinuity of the structural esplanade where it crosses this fault-line; for if the floor of the esplanade is of structural control, it would be opened at whatever level the upper surface of the Red-wall group occupied at the time of the erosion of the canyon. If, on the other hand, the esplanade had been controlled by a former baselevel, its discontinuity at the Toroweap would demand a very late date for the fault, as Dutton concluded when he wrote: "It seems very plain that the outer chasm had been formed and attained very nearly its present condition before the [Toroweap] fault started" (*c*, p. 94). So recent a date of faulting seems inconsistent with the evidence presented in the section on the Pipe spring fault.

Conclusion as to the Origin of the Esplanade. — In view of these various considerations, it seems necessary to conclude that while many partial cycles of erosion may have preceded the long pause during which the broad denudation of the plateaus was completed, only a single uplift and a single down-cutting are recorded in the canyon. It should be noted that Dutton considered this supposition, but rejected it. Speaking of the esplanade, he said: "We might explain it by assuming the rocks of the inner gorge to be much more obdurate than those above. This is true in part, but still the difference in this respect is insufficient. A much more satisfactory explanation is found in the supposition that the broad esplanade of the cañon between the upper palisades was an ancient base-level of erosion" (*b*, p. 121). In another place he explains the difference between the Kaibab and Kanab sections of the canyon in the following manner: "The causes which have produced in the Kaibab a topography differing so widely from that which is seen in the other divisions of the chasm may be readily explained. The Kaibab is now, and throughout the period of evolution of the chasm it always has been, higher than the other plateaus. Corrasion has, therefore, penetrated there more deeply than elsewhere. It has, moreover, laid bare the edges of the softer beds underlying the Red Wall, and the rapid decay of these lower beds has undermined and wasted the Red Wall to a great extent. In the other divisions of the chasm corrasion has only at a very recent period cut below this great series of hard limestones. . . . Besides the greater altitude leading to deeper corrasion, the climate of the Kaibab is moister, and the degrading forces are, therefore, more efficient" (*c*, pp. 257, 258). From the other point of view, it seems as if these several considerations might legitimately be adduced to account for the esplanade as of structural origin; for if differences of structure, altitude, and climate all lead to differences of form between the Kaibab and Kanab sections, there seems to be all the less need for explaining the esplanade in the Kanab plateau by a pause during the uplift. On the other hand, the earlier date of the Kaibab arch must have led to the erosion of the Aubrey limestones on its crest much earlier than the same strata were attacked in the erosion of the canyon further west. The Kaibab must have been trenched, as has been already suggested, to a depth of one thousand or one thousand five hundred feet (probably revealing the lower Aubrey group, but not cutting through it) before the introduction of the canyon cycle, and a broad floor, an esplanade, must have been opened through it, indifferent to structure, at the level of the denuded plateaus on the east and west. Since then there has been time for the deep cutting and rapid widening of the new canyon to destroy all traces of this floor and bring about the correlation of form and structure that to-day so fully characterizes this section of the canyon.

Hints for a Visit to the Canyon. — A few words as to the descent into the canyon from the Coconino rim opposite the Kaibab, with special reference to a sight of the "wedge," may not be out of place. The best geological map of this district is that made by Walcott (*e*, Plate LX.). The Grand View trail, descending from Cameron and Berry's, gives a convenient approach to the apex of the "wedge." Horses for riding and donkeys for carrying a small pack of blankets and provisions can be hired at the hotel; but if the visitor goes on foot, an early morning start should be made, before sunrise, if possible, as the temperature in the canyon is very high over the noon hours during clear summer weather. It would be certainly a great advantage to plan a visit at the time of full moon, so as to be able to use the night hours for at least part of the climb out of the canyon. The Coppermine spur may be easily reached in the morning before the greatest heat sets in, and noon may be passed at its end on the Red-wall platform, studying the "wedge," as exposed in the northern wall, and examining the canyon to the east and west. A light shelter of canvas to keep the sun off would be a great comfort in this work, as shade is scanty and the glare from the bare rocks is fatiguing while one is attentively studying details of structure and form. A field-glass greatly aids and extends observation in all parts of the canyon, for distances are large. A camp for the night may be made in the side canyon next west of the Coppermine spur, where a small stream is found just above the level of the basal Tonto sandstone; but the descent to this spot will be more enjoyed if it is left till late in the day, as the trail down a gulch in the Red-wall cliff is directly exposed to the afternoon sun. A second day can be well spent in descending to the river and in examining the palæozoic floor; or in passing around the Tonto platform at the base of the Coppermine spur so as to enter the next ravine on the east, where the "wedge" seemed to be exposed on the south side of the canyon. When viewed from above, the various slopes and platforms seem very smooth, as if one could walk over them without difficulty; but when actually upon them, the smoothness vanishes; the dimensions of every item of form are magnified far beyond expectation; everything is rough and rugged, and walking is tiresome work. A third day can be given to various problems regarding stratified structures which are here open to observation in a larger way than almost anywhere else in the world. The mere sight-seer may be content with a brief trip down and back, but the geologist who can go as far as the canyon ought to spend several entire days in its depths. We were unfortunately so hurried as to have only an afternoon, a night, and a morning for the canyon.

If the canyon is visited from the north, the trip may be made on horseback or with wagon from Belknap station, Rio Grande Western railroad, southward to Kanab, and thence either southeast to the Kaibab or southwest to the Uinkaret plateau and the Toroweap valley. The former trip repeats the views seen from the Coconino rim, but it is without the advantage of good trails by which the descent may be made to the river. The latter takes the observer to a great field of volcanic phenomena as well as to the brink of the canyon at a most interesting point. After recent rains, water-pockets can be depended on for camping near Vulcan's throne; but if the season has been dry, water must be brought from Oak spring on the Uinkaret. Although this is troublesome, it is entirely feasible. Two nights and a day are the shortest time that should be wisely allowed to this wonderful spot: it was a real hardship that our party had only a day for the ride from Oak spring to Vulcan's throne and back.

Former Climates of the Grand Canyon District.

Diverse Opinions of Early Observers. — The several opinions expressed by Newberry, Powell, and Dutton as to the former climates of the region under discussion seem to me difficult to maintain, so many are the doubtful elements in problems of this class. Newberry inferred a former greater rainfall (p. 47), apparently because of the immense amount of denudation that has been accomplished; but until more is known as to the time occupied in the great denudation, it is impossible to make inferences as to its rate, and hence as to the strength of the eroding and transporting agencies, and the rainfall that excites them. Powell inferred a long-maintained arid climate, because "in a region of country where there is a greater amount of rainfall, the tendency is to produce hills and mountains, rather than plateaus and ridges, with escarpments" (*a*, p. 204). It may be urged against this view that escarpments of a strength appropriate to their capping layers occur in better-watered regions, as in the Catskill mountain front of eastern New York, and in the Swabian Alp of southern Germany; and that the cause of the great cliffs of the Grand canyon district is to be found chiefly in the massive thickness of the resistant strata that guide them, and in the weakness of the underlying strata that sap them. Truly, the sharpness of the cliffs is highly suggestive of aridity, but a relatively short arid period would suffice to sharpen the cliff profiles, even if they had been somewhat dulled by a previous humid period.

The narrowness of the canyons, so generally explained by the aridity of the plateaus through which the vigorous Colorado flows, certainly finds a large part of its explanation also in the recency of the uplift by which the canyon cutting was initiated, and in the massiveness of the resistant layers by which the canyon walls are defended. The side canyons by which the plateaus are dissected are not insufficient in number even for a moist climate; they are much more numerous than the perennial side streams. The latter are notoriously rare: the former are present in good number, and in wet weather they are actively washed by their temporary floods. It is true that the side canyons are of so steep a descent along their floors that they lose much of their depth at a moderate distance back from the main river; but this may be a consequence of recent uplift as well as of slow corrasion. The side canyons branch frequently enough to satisfy an active drainage system, and certainly there is no deficiency of ramifying valleys on the higher uplands where the surface is so thoroughly and maturely dissected. It is the steep grade of the waste on the floors of these valleys that suggests a development under an arid climate, and such a grade would be soon acquired under a dry climate even if the valleys had once been cut somewhat deeper under a moist climate. Hence, even in the more recent past of the canyon cycle, a humid climate seems no more impossible than unnecessary, and in the more distant past of the plateau cycle, climates of any and all kinds might have prevailed, as far as the present topography of the Grand canyon district is concerned.

Moist Miocene and Arid Pliocene Climates. — In contrast to Powell, Dutton concluded that the Miocene (plateau cycle) was humid. This opinion seems to have been based partly on the occurrence further north of extensive fresh-water deposits of Miocene age, usually interpreted as having been laid down in large lakes, whose existence pointed to a good supply of rainfall (*c*, p. 223), and also on the apparent desiccation near the beginning of the Pliocene (canyon cycle) of certain branches of the Colorado, whose previous existence implied the continuance of a good water supply, just as their later disappearance implied its cessation (*c*, pp. 99, 201, 223) ; the arid climate thus introduced continued to the present day, except for the occurrence of an inferred pluvial period corresponding to the glacial period elsewhere.

Other interpretations seem to me possible for several of the facts here brought forward. I have elsewhere presented some considerations regarding the possible explanation of at least some of the fresh-water Tertiary deposits of the Rocky mountain region as fluviatile rather than as lacustrine formations (*b*, p. 360), and in so far as this alternative explanation is found applicable, the evidence above quoted for the humidity of the plateau period will weaken. The argument for a change from humid to arid climate, based on the apparent disappearance of certain streams, seems to me open to serious question ; it is considered in the next section. The ravines that are adduced by Dutton as the evidence of a brief Pleistocene pluvial period appear to be open to explanation under as arid a climate as prevails to-day, as will be specially considered in the next section but one. Thus the climatic history of the district becomes extremely uncertain. Whatever conclusions are reached as to the climatic conditions of any period of past time — the glacial period, for example — in surrounding regions may be permitted for the Grand canyon district, but no special climatic conditions are demanded by local evidence. Yet among the several opinions quoted above, the long-enduring arid climate suggested by Powell seems to me the most probable, because for a long time the Grand canyon district has lain to leeward of a mountainous area, and during much of this time the district stood lower than it does now, while the mountains to windward were higher.

THE TOROWEAP. — The Toroweap (T, Figure 1) has already been referred to as a valley that has been eroded along or near the southern part of a long fault-line that comes from the northeast past Pipe spring ; it is part of the boundary between the Uinkaret and Kanab plateaus. The peculiar feature of the valley now in evidence is its shallowness ; for its broad floor leads forward to the level of the esplanade and shows in its surface form hardly any sign of incision to a deeper level. Dutton infers from this that the stream by which the valley was originally eroded became extinct about the time of the latest upheaval of the region, after which the inner canyon was cut down beneath the esplanade by the main river, whose water supply in distant mountains had not been cut off (*c*, p. 99). There are two arguments against this view. First, a number of side canyons in the neighborhood of the Toroweap, of similar or smaller drainage area and equally dry, are cut down to essentially accordant junction with the bottom of the main canyon. A small valley of this kind is seen to enter the main canyon from the south at a short distance west of the South Toroweap;[1] a view of its upper part is included in a drawing made by Holmes to illustrate the dikes in the canyon wall (Dutton, *c*, Plate XVIII.). Although the drainage area from which the wet-weather stream is here gathered is but a small fraction of that which supplies the floods of the Toroweap, this short side valley is cut deep below the esplanade level for several miles back from the inner canyon wall, and as its stream line descends with the steep grade appropriate to short lateral canyons, it makes an essentially accordant junction with the Colorado. A view of the inner canyon from near Vulcan's throne (Dutton, *c*, Plate XVII.) has already been referred to as showing the accordant entrance of two side canyons into the main canyon in the neighborhood of the Toroweap. The same relation obtains in the case of an unnamed side canyon, coming from the north twelve miles east of the Toroweap: its drainage area is similar to that of its high-floored neighbor, yet it is cut down so that its temporary floods may join the main river in perfectly accordant fashion, as far as one may judge from the topographic map of the locality. Many other examples of this kind might be given, as could be inferred from what has already been said in a previous section as to the generally accordant junction of side and main canyons. It, therefore, does not seem possible to ascribe the failure of erosion in the Toroweap to the desiccation of a once permanent stream; for in that case all the neighboring streams in small side canyons must also have been desiccated, and should have high floors; yet as a matter of fact their streams have not ceased to erode effectively.

Secondly, some local obstacle to erosion in the Toroweap would suffice to explain its peculiar form, and such an obstacle certainly occurs there, for the broad floor of the valley has been heavily and repeatedly sheeted over with floods of resistant lava, supplied by the magnificent lava cascades from the Uinkaret, as pictured in one of Holmes's most effective drawings (Dutton, *c*, Atlas, sheet V.). The occurrence of the lava flooring is fully recognized by Dutton, who wrote: "There is reason to believe that at some prior epoch it [the Toroweap] was cut a few hundred feet deeper than its present floor, and was subsequently built up by many floods of basalt coming from the cones on the Uinkaret and by considerable quantities of alluvium washed from its cliffs and overlooking mesas" (*c*, p. 92). We may therefore conclude that in the early stages of the canyon cycle, when the intermittent side streams had cut down their canyons into the Red-wall group and the canyons had already widened somewhat through the sapping of the upper Aubrey cliff-makers by the weak red beds of the lower Aubrey, the Toroweap was flooded with lava, while most of its neighbors remained free from volcanic interference. The streams in the latter continued to deepen their courses, while deepening was practically stopped in the Toroweap. But just as the main canyon has widened above the resistant floor of the esplanade, so the Toroweap continued to widen, hence it is to-day normally broad but abnormally shallow. It is a "hanging valley" because of local volcanic interruption of the normal work of canyon-cutting.

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[1] I have used this name for a valley corresponding to the Toroweap and apparently structurally continuous with it but south of the canyon.

Directly opposite the Toroweap is a similar high-floored valley (*c*, p. 99), splendidly exhibited from Vulcan's throne, and already referred to as the South Toroweap. Like its northern fellow, it is floored with lava near the main canyon, on which it opens close to the esplanade level (Dutton, *c*, Plate XVIII.). Hence its deficiency of depth again seems to be best accounted for by the difficulty of wearing away its lava sill, an accidental and purely local detail, rather than by a failure of rainfall, which must have been general.

Dutton mentions several other high-floored valleys, which he classes with the Toroweap as indicating a decrease of rainfall at the beginning of or early in the Pliocene (canyon cycle). One of these is the Queantoweap, which follows the Hurricane fault along the boundary between the Uinkaret and Shivwits plateaus (*c*, pp. 99, 115). Not having seen this valley, I shall not venture to express an opinion about its origin, yet it may be noted that a small flow of lava near its mouth is marked on the geological map (Dutton, *c*, Atlas, sheet VIII.); and judging by the great lava cascades that plunge into the valley (*ibid.*, *c*, p. 116), some lava may lie concealed beneath the alluvium of the valley floor. A third high-floored dry valley mentioned by Dutton is that on the summit of the Kaibab uplift (*c*, pp. 194, 197, 223) already discussed and explained as a series of independent anticlinal valleys, and thus seeming to be within reach of explanation without recourse to climatic change. A fourth example is House-rock valley (*c*, p. 201), which has already been referred to as a normal subsequent valley worn on weak monoclinal strata. Taken altogether, the lava-floored valleys, the anticlinal valleys, and the monoclinal valley seem to be indifferent witnesses as to changes of climate in the past.

THE PLUVIAL EQUIVALENT OF THE GLACIAL PERIOD. — There is much probability that the rainfall over the Grand canyon district was increased at those times when ice sheets and glaciers were formed over other parts of the continent; yet it seems to me difficult to find independent proof by purely local evidence that such has been the case. Dutton, however, suggests that evidence of this kind is to be found in the ravines of the Kaibab plateau, concerning which he finds "no conjecture so satisfactory as that which supposes that during the glacial period the rainfall was sufficient to sustain living streams in these ravines and that they were then carved by running water" (*c*, p. 196). The same conjecture is thought to hold true for the ravines of the Paria plateau (*c*, pp. 202, 228). Nevertheless, it is difficult to find valid reason for ascribing the erosion of these ravines only to the glacial period, for it seems admissible to conclude that they can have been in large part eroded by the intermittent streams of a climate as arid as that of to-day. The maturity of many of these ravines in resistant strata indicates that, besides glacial time, some of preglacial and all of interglacial and of postglacial times must have been needed for their erosion; hence instead of ascribing them to the glacial period alone, their beginning may be carried back even into the later part of the cycle of the great denudation, as has already been suggested on page 141. Moreover, existing processes do not seem to be inoperative. The stream beds in the lower ravines of the Kaibab bear every mark of being strongly flushed by occasional wet-weather floods. Well-defined fans of coarse and fine waste extend forward from the mouth of the ravines at the eastern base of the Kaibab into House-rock valley, as has been already stated; and a torrent fan was seen at the western base where the road from Jacob's lake descends toward Fredonia. However slow the erosion of the ravines may now be, it is still going on; indeed, the scantiness of vegetation makes the removal of waste so easy that it may be questioned whether rain and stream work is not advancing here at a comparatively rapid rate, — a rate that very likely far exceeds that which prevails in the peat-covered uplands of much moister regions.

Volcanic Phenomena.

Our interest was frequently attracted by magnificent displays of volcanic phenomena in various parts of the Grand canyon district, but we had no time to turn from our route to study them. A few notes on the more striking things are here presented in the hope that they may prove of service to more leisurely travellers.

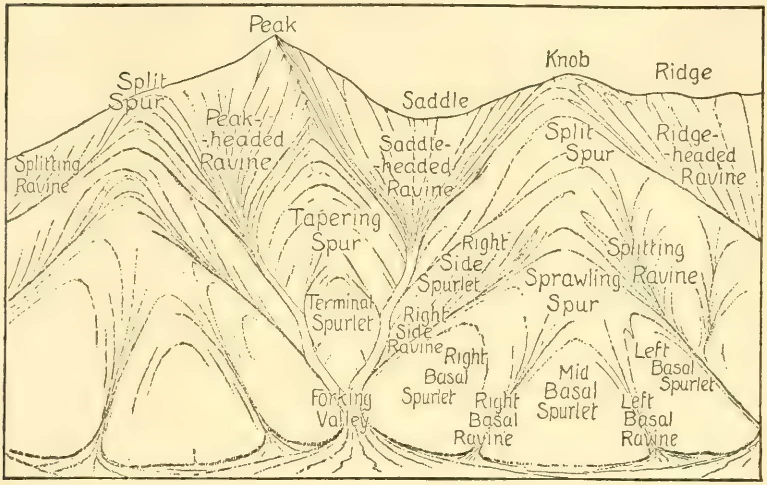
Peak
Split Spur
Peak-headed Ravine
Splitting Ravine
Saddle
Saddle-headed Ravine
Knob
Ridge
Split Spur
Ridge-headed Ravine
Tapering Spur
Right Side Spurlet
Splitting Ravine
Sprawling Spur
Terminal Spurlet
Right Side Ravine
Right Basal Spurlet
Mid Basal Spurlet
Left Basal Spurlet
Forking Valley
Right Basal Ravine
Left Basal Ravine

FIGURE 17.

Diagram to illustrate a proposed terminology of spurs and ravines. Constructed from several sketches of the western side of Mt. San Francisco, a dissected volcano.

The dissection of Mt. San Francisco, as seen from the wagon road that runs northward from Flagstaff along the western base of the mountain, suggested a simple terminology for spurs and ravines that might perhaps be serviceable in detailed descriptions of mountain forms. The scheme is illustrated in the accompanying figure, 17, which repeats some of the features illustrated in the diagram of the Permian scarps (Figure 9). I shall hope to return to this phase of morphology at some future time. The young ash cones, still holding unbreached craters, were numerous in the volcanic field north of Mt. San Francisco (Figure 18). About ten miles west of Hull spring (on the Flagstaff-canyon road) a large ash cone was seen with a great breach in its eastern

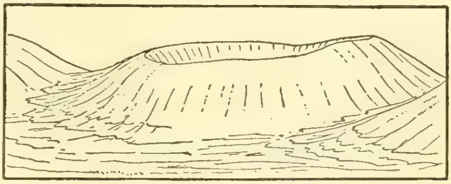

FIGURE 18.

An ash cone and crater, north of Mt. San Francisco and east of Hull spring.

slope, a promising specimen for the study of the structure of such cones. One of the northernmost of the eruptions in this field (Y, Figure 1) seems to be also one of the youngest; it lay several miles south of the rough trail that we followed eastward from Hull spring to the Flagstaff-Tuba road, and as seen at that distance it seemed to form a ragged black mesa, two or three hundred feet high. The various relations of lava flows to small valleys were beautifully exhibited in the same district. In one case a flow banked against the scalloped escarpment of the upper Aubrey, and a little waterway has since been eroded along the line of junction, with yellow-gray limestone on one side and black lavas on the other; this was well seen on the canyon road, a few miles north of Hull spring. Further east, we followed valleys eroded to a depth of two or three hundred feet in the Aubrey layers, and then floored with streams of lava from some neighboring cone. In one narrow valley of this kind, the wash of waste from the walls seems to have prevented the formation of new waterways along the lava margin; here the present stream bed lies for a distance on one side of the valley, then trenches obliquely across the lava and follows its other side for a stretch. In a broader valley, the lava surface was untrenched, and new waterways ran persistently along its margins, this being evidently the incipient stage in the formation of a lava mesa. At Lockett's tank (probably several miles north of Black tank of the topographic map) a narrow canyon of moderate depth in the Aubrey limestone has been filled nearly to its brim with a slender but heavy lava flood, but at present the stream has re-excavated part of its valley, consuming the terminal part of the lava flow for half a mile or more, although leaving scraps of lava here and there, frozen to the walls; and at the head of the new valley is an abrupt fall from the surface of the lava that still remains (Figure 13). Here the wet-weather floods have scoured a basin, in which water remains long after the supplying storm has cleared away; cattle tracks converge on the dry upland from all sides towards this tank.

A narrow dike was noted on the west-facing slope of the Triassic escarpment, just south of the valley of the Moencopie and not far from Tuba; the dike formed a sharp ridge, quite unlike the more tabular forms normally associated with the escarpment.

The great lava cascades that descend from the Uinkaret into the Toroweap and even into the canyon itself are among the most magnificent geological phenomena of the region. Our camp by Oak spring, south of Mt. Trumbull, was at the scarped edge of one of the younger lava flows of the Uinkaret; and the youngest flow of that volcanic field lay a mile to the east (Powell, *a*, p. 131; Dutton, *c*, p. 111, Atlas, sheet IX., lower view); we crossed it on the way down into the Toroweap, and came back by a trail that ascended one of the great lava cascades. A young ash cone stands on the tabular top of Mt. Trumbull, whose mass is but the remnant of a once much larger lava mesa; the young cone was peculiarly placed near its southeastern end of the mountain. A series of cones and black lava flows were passed in the northern part of the Uinkaret block, between the western scarps of the Shinarump mesa and the Hurricane ledge. The lava-floored valley above Workman spring has already been mentioned. The canyon of the Virgin just after the river emerges from the Hurricane ledge is cut in lava for several miles. A side canyon, about two miles south of Toquerville, revealed a fine section of a lava flow lying on a coarse gravel which partly filled a small valley, all shown in a single section. These latter items, along with many others, would be included in the special study of the Toquerville district, which may be so highly commended as a subject for a summer's field work.

Summary.

A high degree of consistence among the consequences of various associated theories is justly regarded as strong proof of the correctness of the theories themselves. Each of the earlier students of the Grand canyon district probably reviewed his conclusions to see that they were mutually consistent, and published only those that survived this test. As the progress of exploration and the advance of earth-science furnished more and more items in the sequence of events that make up the history of the district, the interlacing of more and more elements seemed to give at once greater difficulty to the problem and greater certainty to its solution. Dutton in particular appeals this aspect of the method of proof, and truly the successive steps in his thesis are strongly enchained. Yet it now seems possible to arrange a new sequence for some of the events by which the present order of things has been produced: a sequence which differs from that announced by previous observers in several particulars, as presented in the concluding summary below, although still holding to the main outlines of the geological history of the region as presented in the several governmental reports. The question then arises, where shall the permanent truth be found among all these suggested possibilities? Further exploration, and more particularly detailed study of certain special problems, will in due time review all the explanations now offered and select the survivors from among them. The work of new observers is especially needed in the examination of certain structures, as in the neighborhood of Toquerville, and between Pipe spring and the Toroweap; and in the discussion of dates of certain past phenomena, such as flexing, faulting, and uplifting; and in the discovery of the origin of the drainage system and the character of the climate of past periods. Whether the conclusions here announced shall then stand or fall in whole or in part, it would be a great reward to the writer if they might afford later students of the region even a small share of the aid that he has derived from the earlier work of Newberry and of Powell, of Gilbert and of Dutton.

The results reached in the foregoing pages may be summarized as follows. There is some probability that the San Rafael swell, like the Waterpocket flexure, is of pre-Tertiary origin. The other deformations of the region, both flexures and faults, are almost exclusively of much earlier date than the canyon cycle, and they may have been formed relatively early in the erosional history of the district. The total denudation of the region thus far accomplished may be considered in two parts, of which the first — the great denudation — was far advanced before the general uplift by which the second — the erosion of the canyon and the stripping of weak strata from the plateaus — was introduced. But the great denudation was complicated by repeated movements, after each of which the processes of erosion may have reached an advanced stage before the occurrence of the next series of disturbances. It is only by an analysis of these repeated movements and revived erosions that the origin of the drainage system can be determined. As far as this analysis can be attempted at present for the Grand canyon district, the side streams seem to be of various origins, except that none of them appear to be antecedent. The Colorado itself may be in part antecedent to some of the many dislocations that the district has suffered, but it seems to be for the most part consequent on the displacements caused by faulting in the later part of the great denudation, and on the form that the surface had assumed at that time. The floor of the Toroweap valley is higher than the neighboring valley floors, because it is sheeted with heavy lava flows which have effectively withstood the intermittent erosive efforts of wet-weather floods. The past climate of the region cannot be safely determined; a change from a humid to an arid climate at the close of the Miocene does not appear to be demanded by the facts that have been appealed to in its support.

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EXPLANATION OF PLATES.

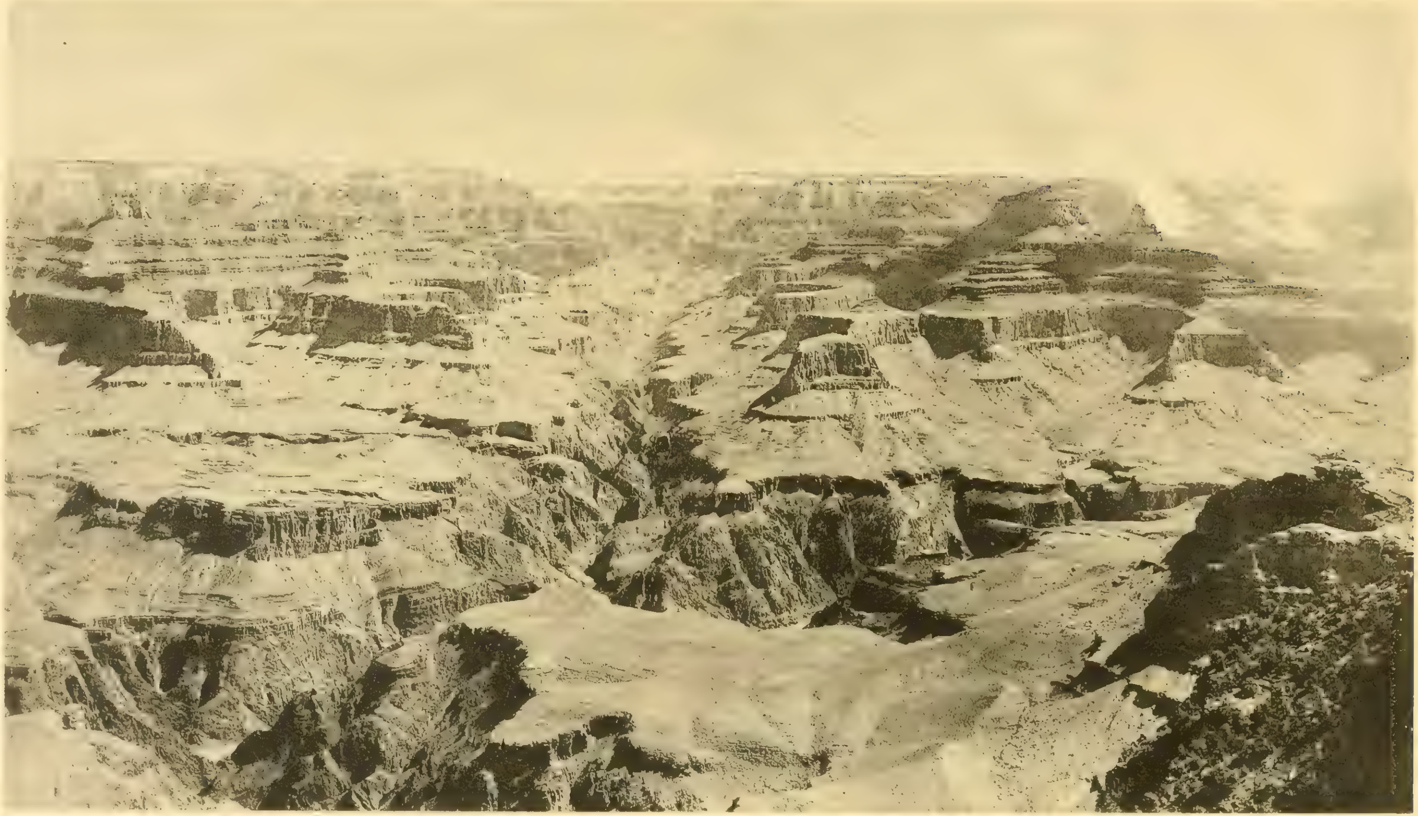
PLATE 1.

General view of the Colorado Canyon, looking about north from O'Neill's point to the Kaibab plateau. Copyright photograph by Detroit Photographic Co.

PLATE 2.

A. A shallow valley floor in the Coconino forest, south of the Colorado canyon; a hill and drying-ground of the farmer ant in the foreground. Photograph by Dr. H. E. Gregory.

B. A boulder of Shinarump sandstone perched on a pedestal of weak Permian shales at the base of the Shinarump bench, beneath Vermilion cliffs, Paria plateau, southwest of Lee's Ferry. Photograph by Dr. H. E. Gregory.



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C. HARTLAUB. The Comatulæ of the "Blake," with 15 Plates.
H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea of the "Blake."
A. E. VERRILL. The Alcyonaria of the "Blake."

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of ALEXANDER AGASSIZ, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

Illustrations of North American MARINE INVERTEBRATES, from Drawings by BURKHARDT, SONREL, and A. AGASSIZ, prepared under the direction of L. AGASSIZ.

LOUIS CABOT. Immature State of the Odonata, Part IV.
E. L. MARK. Studies on Lepidosteus, continued.
" On Arachnactis.
R. T. HILL. On the Geology of the Windward Islands.
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" The Eyes of Deep-Sea Crustacea.
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H. J. HANSEN. The Cirripeds.
W. A. HERDMAN. The Ascidians.
S. J. HICKSON. The Antipathids.
W. E. HOYLE. The Cephalopods.
G. VON KOCH. The Deep-Sea Corals.
C. A. KOFOID. Solenogaster.
R. VON LENDENFELD. The Phosphorescent Organs of Fishes.
H. LUDWIG. The Starfishes.
J. P. McMURRICH. The Actinarians.
E. L. MARK. Branchiocerianthus.
JOHN MURRAY. The Bottom Specimens.
P. SCHIEMENZ. The Pteropods and Heteropods.
THEO. STUDER. The Alcyonarians.
M. P. A. TRAÜTSTEDT. The Salpidæ and Doliolidæ.
E. P. VAN DUZEE. The Halobatidæ.
H. B. WARD. The Sipunculids.
H. V. WILSON. The Sponges.
W. McM. WOODWORTH. The Nemerteans.
" The Annelids.

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AT HARVARD COLLEGE.
VOL. XXXVIII.

GEOLOGICAL SERIES, Vol. V. No. 5.

THE GEOLOGY OF THE NORTHEAST COAST OF LABRADOR.

BY REGINALD A. DALY.

WITH THIRTEEN PLATES.

CAMBRIDGE, MASS., U. S. A.:
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No. 5.— *The Geology of the Northeast Coast of Labrador.*

By Reginald A. Daly.

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(*Bearings refer to the true Meridian.*)

Introduction.

In the late summer of 1899, Mr. Huntingdon Adams, of the class of 1901 at Harvard, paid a flying visit to the coast of northern Labrador. He was so impressed with the beauty of the fiords and mountains of the country that he conceived the idea of organizing a party which should spend the following season exploring in the same region, with intent to bring back more definite information regarding its general geography than had yet been obtained. With the advice and aid of Prof. E. B.

Delabarre of Brown University, the scheme was successfully carried out, and a most profitable and enjoyable summer spent by those who participated in the expedition. The party also included Messrs. H. B. Bigelow, L. B. McCornick, and H. W. Palmer, undergraduates of Harvard. I was asked to accompany them and record any geological observations that might be possible on a trip of the kind proposed. Rather more was accomplished in this direction than was hoped for at the outset, and the results are believed to be of sufficient interest to warrant some degree of detail in their recital. The following pages are intended to afford a brief treatment of the more important problems met with during the summer; some of these have found solution, others will, it is hoped, be more clearly defined for future visitors to a little known shore.

The equipment of the expedition was quite modest but sufficed for most needs, excepting that for rapidity of travel. The vessel selected for the journey was the "Brave," a forty-ton fishing schooner, just rebuilt and specially fitted up to be the summer home of the party and of the four seamen employed to take the larger share of the navigation required. Thoroughly staunch and clean, and commanded by a skipper of unusually wide experience and close knowledge of the thousand dangers of this coast, the craft was found to be both safe and comfortable. The instrumental outfit included five aneroid barometers; two ordinary thermometers; a corrected thermometer lent by the Superintendent of the United States Coast Survey, from whom there were also obtained two sets of salinometers and a hydrometer cup; four Negretti-Zambra deep-sea thermometers, and five hundred fathoms of piano-wire, lent by Mr. Alexander Agassiz; a sextant, lent by Brown University; and a prismatic compass. The tools in trade of a botanist, an ornithologist, and a geologist, were likewise represented on board. Professor Delabarre worked assiduously on the flowering plants encountered on the route, and collected freely from the cryptogamic vegetation which is so striking a feature of the coast. Mr. Bigelow's former experience enabled him to seize quickly the peculiar ornithological features of the coast, and he has added several species new to its list of birds.[1] The writer, though chiefly occupied with the general geology ashore, spent some time in a limited study of the hydrography of the Labrador Current. Before proceeding to the discussion of results, it will be well to give a brief account of the itinerary. By so doing, the conditions under which the observations were carried on may be most easily understood.

---

[1] Cf. Auk, 1902, xxvii. pp. 24–31.

Itinerary of the Cruise.

On June 25th the "Brave" weighed anchor at St. John's, Newfoundland, and sped rapidly northward with a fair wind to about Lat. 49° 20′ north. The next day a strengthening gale decided our captain to run for shelter at Greenspond. Compelled to remain there until July 2d, we had leisure to examine the hummocky islands of Laurentian porphyritic granite and to study the hard conditions of life in a town of Newfoundland fisher-folk. We came to a full understanding of the fact that the dangerous sea more readily gives them livelihood than the soilless ledges which need imported earth before they yield a useful vegetable. A quick run without incident, save a halt at Change Island, brought us to Cape Bauld at noon on July 4th. Here we were destined to disappointment in the hope that the Straits of Belle Isle might be crossed and "the Labrador" attained without delay. The northern half of the strait was found to be impassable on account of a broad stream of pan-ice; the "Brave" beat back and anchored at nightfall in Kirpon Harbor which lies in the "tickle" east of Kirpon Island.

The next day, from a hill north of the harbor, we had a remarkably striking view of drift-ice streaming west-southwest into the strait and southward past Belle Isle along the east coast of Newfoundland. The Labrador current was a vivid reality to us as we watched the truly majestic procession of these dazzling migrants from a polar sea. That day closed with no indication that our snug harbor would be threatened with an invasion, but we came on deck the next morning to find ourselves in an Arctic landscape. The schooner was firmly wedged in among the heavy pans of ice which during the night had quietly drifted into the "tickle" under the impulse of north wind and flood current. The unusual thickness and quantity of the ice, coupled with the steady character of the north or "up" wind, caused our detention in this harbor until the morning of the 13th. These seven days were spent among the picturesque hills and valleys in the vicinity and among the exquisitely tinted ice-floes. Among the sedimentary rocks which compose Kirpon Island, Jacques Cartier Island, and the mainland roundabout, an interesting boulder basalt, with pillow structure, was discovered. It is hoped that a description of this typical occurrence will be given on another occasion.

Along with more than a hundred other schooners from the many anchorages of this indented coast, the passage of the straits was finally made. Not the least memorable scene of the summer was this brilliantly sunlit expanse of water covered with the great fleet and with a long train of icebergs, two of which were probably the loftiest seen during the cruise.

Headed by the wind, immersed in thick fog, and trapped once more by ice-floes, we lay at anchor in Assizes Harbor on the north side of the straits until the 17th, when we escaped again and ran sixty-five miles to Seal Island. Three days' delay by ice and head winds here, and three more at West Bay Head on the south side of Hamilton Inlet, completed the first month of the cruise and evoked many remarks from our skipper on the extraordinary difficulty of "getting down" the coast this season. The failure of westerly and southerly winds and the massive character of the drift-ice so late in the summer were alike unparalleled in his thirty years' experience on this coast.

"The extraordinary smoothness of the sea covered by drift-ice, even when the pans are widely spaced, is truly astonishing to one making his first voyage in such waters. His sailing ship may be favored with a fresh breeze and yet the ocean surface be quite level, save for the minute rippling characteristic of a small pond ruffled by a summer breeze; ground-swell does not exist. It is a matter of common knowledge among the fishermen of the Atlantic Labrador coast that the Labrador current, or 'tide,' as they invariably express it, often shows high velocity, although its surface, for a length of a thousand miles and a breadth variable but at times as much as three hundred miles, is covered with loose pan-ice. At such times, the wind is, or has just been, strong and from a northerly quarter. We are justified in believing that the pans act as the sails which, in ice-free waters, are represented by wind-waves. Floes and pans project above the surface from one to twenty feet or more. They may be expected to exert a coercive force on the film of relatively fresh water derived from the melting of the ice in contact with the heavier salt water beneath. According with the behavior of such 'dead water,' as described by Nansen and others, the light surface layer will tend to move *en masse* and in the direction of common pull exercised by the wind-driven masses of ice. By reason of friction the motion will be communicated to lower layers of the sea. This cause of surface currents is of importance to the theory of movement of those polar waters which, for several months after the winter ice begins to break up, are free from larger wind-waves. Deprived of its chief sails, the Labrador current, always sensitive to wind conditions and at times subject to temporary reversal with contrary winds, yet preserves and perhaps exceeds during the period of ice-drift, the average velocity of current-flow for the year."[1]

On the 24th, the mouth of Hamilton Inlet was crossed. Ice afforded little trouble henceforth, but head winds prevailed; so that, at frequent intervals, we were compelled to drop anchor and wait for the short-lived favorable winds on which our progress against the south-flowing current depended. The longest run made between the straits and Hebron, a distance of eight hundred miles, was only fifty-three miles in length. Twenty-two halts of greater or less duration were made on this part of the journey. Nachvak Bay, eleven hundred miles from St. John's, and the objective point of the expedition, was not reached until August 21st. Thus but a small portion of the summer remained for the exploration of the high mountains in the north. At the end of two weeks we were forced to weigh anchor and begin our homeward journey.

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[1] Science, Nov., 1900, vol. 12, p. 688.

Disappointing as our rate of progress was in this one respect, there yet remained the advantage that, with so many opportunities to land in southern Labrador, we were able to sample, with fair continuity, the geology of a coast-line which is in every part in need of investigation. In fact, some of the most interesting problems of the summer would have been necessarily left untouched, if our early ambition to make a rapid northward run had been satisfied. The return to St. John's was accomplished in four weeks, during which time, several gaps in the required series of observations were filled up. We dropped anchor for the last time in the early morning of Oct. 3d, having been out a few hours less than a hundred days. In that period, we had been thirty-nine days at anchor against our will, but there was, at each detention, always the consolation of an opportunity to get a view, however hurried, of a region full of novelty and at times no less interesting than the goal of our endeavor, the Torngats of the north. At the same time, it is clear that nothing more than a reconnaissance could be made at any of the anchorages.

Observations on Topography and Bed-rock Geology.

The general form and composition of the old-mountain plateau of Labrador have already been admirably treated by Packard,[1] Bell, and Low, and by the writer of the article "Labrador" in the Encyclopædia Britannica. These and earlier writers agree that the northeastern coast of the peninsula marks the edge of the great Archæan shield of North America; and, further, that, if exception be made of the "Domino quartzite," the Ramah slates, and certain occurrences of sedimentary rocks in Nachvak Bay, the bed-rock of the coastal belt is throughout crystalline. Gneisses, intrusive granites, syenites, gabbros, and traps prevail from the Straits to Cape Chidley.

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[1] A bibliography relating to works on Labrador is published in "The Labrador Coast" by A. S. Packard, Jr. New York and London, 1891.

The results of last summer confirm this general view, but it was found that sedimentary formations not heretofore described appear in great development on the shield border. At Pomiadluk Point, at Aillik Bay and in the Mugford region, as well as in the long stretch from Saeglek Bay to Ramah, the crystallines form the foundation to stratified series of very diverse character. These merit particular notice in a sketch, however brief, of the general geology of the coast. The extrusive lavas of the Mugford series, the intrusive traps which occur in astonishing profusion in the 700-mile belt, and the gabbros of Paul's Island and vicinity will also claim attention. It will be shown that a correlation of the strike-directions of schists and sediments indicate in the coastal border a decided N.W.–S.E. trend which corresponds rather closely with the average trend of the shore-line. Finally such observations as have been made on the topography and physiography will be described in connection with the bed-rock geology.

From the Straits of Belle Isle to Paul's Island.

General Topography. — As far north as Cape Mugford, over five hundred miles from the Straits, the edge of the plateau is in plan extremely ragged. Numerous fiords, ria-like bays and a vast archipelago of outlying islands or skerries form a coastal fringe. The similarity of landscape is so great that Forbes's description of the coast of Norway on the route from Trondhjem to Bergen may be repeated for this portion of Labrador. A series of inlets penetrates "in all directions a low, bare, rocky land, partly island, partly continent, nowhere rising but to a very small height above the sea, and so monotonous in character, and destitute of long reaches, or natural landmarks, as to seem to require an almost superhuman instinct for its pilotage."[1]

The contours of the islands are repeated in the hills of the low plateau of the mainland; the inlets, sounds, and narrow channels among the islands (the "tickles" of the fishermen) represent the submerged equivalents of the valleys on the mainland. From any commanding hill on island or mainland, the eye ranges far and wide over a surface showing everywhere the evidence of universal and profound glaciation. Unobscured by forest, soil, or thick drift, and singularly expanded because of the crystalline clearness of the atmosphere, the view typifies that which may be had in the Laurentian Highlands of Canada or in the Archæan of the Scottish Highlands. It is a great wilderness of innumerable rounded, ice-worn hummocks generally gneissic in composition. Among the *roches moutonnées* lie equally countless ponds and bogs connected by the small streams of a most disordered drainage.

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[1] J. D. Forbes, Norway and its Glaciers, Edinburgh, 1853, p. 104.

In sheltered places and at the higher altitudes the snow lies throughout the year. On Pomiadluk Point, two ravines, running from about the four hundred-foot contour to the eight hundred-foot, a distance of four hundred yards in each case, were found to be occupied with snow to a depth of from fifty to seventy-five feet. Typical transverse crevasses ten to twenty feet in depth and yawning widely at their mouths indicated by their attitude and down-stream curvature that the snow was moving, glacier-like, down the slope. No blue ice was seen, but it is possible that such existed in the deeper parts. Though many such banks were found on the coast, especially on the higher mountains of the north, none of them so closely approximated a true glacier in look as these on Pomiadluk Point.

The existence of the coastal fringe suggests at once that the plateau has been drowned by recent subsidence. Yet, in view of the evidence derived from the study of hanging valleys and fiords in Norway, Alaska, and elsewhere, it is open to question whether the same glacial erosion which has so conspicuously moulded the mainland may not be as well responsible for the depressions on the plateau-border now occupied by salt-water. In other words, the differential erosion of an ice-sheet extending out beyond the island-zone may have excavated these depressions which would permit of the entrance of the sea when the ice had left the country. It is significant that where, on this coast, north of Hebron, glacial erosion was confined to the main valleys, the fiords corresponding to the latter are magnificently developed but the islands largely fail. The sounds and tickles do not now present the systematic relations of drowned river-valleys; such irregularity as is known to characterize the erosive activity of valley glaciers is without doubt represented beneath an ice-cap and might leave just such channels below sealevel as a memorial of that fact. It cannot yet be asserted that differential glacial erosion has contributed more to the present outline of the Labrador coast than simple drowning, but it has certainly affected the original preglacial form of the plateau to a great extent. In any case, it is important to recognize in a systematic discussion of shore-lines, a type wherein glacial erosion, independently of crustal movement, may produce an island-zone similar to that of a "drowned coast."

While this glaciation has given a monotonous though not unpleasing character to the plateau, the headlands and islands of the coast exhibit in detail a great variety of form. Sea-cliffs, benches, sea-chasms, fretted ledges, beaches, gravel-bars, spits, and narrow coastal plains, all belonging to the zone of postglacial emergence, add much to the scenic quality and interest of a voyage along the coast. In this rugged soilless belt, it is literally true that he who runs may read, and if he be a student of geological processes, will find perpetual instruction from the coastal views.

THE GEOLOGY. — South of Hamilton Inlet, the bed-rock seems to belong entirely to the crystalline complex (Plate **11**). Assizes Island and the mainland at the mouth of the St. Charles River, are underlain by greatly contorted biotite and hornblende gneisses, biotite schists and amphibolites; quartz and pegmatite veins occur in large numbers. Similar rocks were found at St. Francis Harbor on Granby Island. The geology is further much complicated by the frequent occurrence of large areas of massive and gneissoid granites and diorites and by an equally persistent appearance of trap-dikes. The coarse gneissoid granite of Great Caribou Island on the south side of St. Lewis Sound, was remarked for its development of ilmenite in anhedrons from one eighth to one half an inch in diameter. The mineral showed a perfect development of the octahedral parting which was again seen in the ilmenite crystals an inch in diameter that are plentifully distributed in a vein of graphic granite at Rogue's Roost, Seal Island. This vein is twelve feet in average width and is beautifully exposed for some three hundred feet of length. Seal Island is chiefly composed of coarse hornblende granite cutting coarse diorite and is itself cut by pegmatites, fine-grained aplites and numerous wide dikes of hornblende biotite diorite.

Drift-ice prevented our anchoring in Domino Harbor and thus I had no opportunity of seeing in its classic locality the "Domino Gneiss" of Lieber,[1] nor the quartzitic rock described by Packard[2] and interpreted by Bell[3] as representing a remnant of the Huronian in eastern Labrador. In a private communication to the writer, Packard states that he is inclined to agree with Bell that the latter rock is in reality an arkose. At Pottle's Cove, West Bay, which Packard's map places in the zone of the Domino Gneiss, a peculiar and striking rock-type has large development. It is a medium-grained to fine-grained gneiss weathering under the almost universal covering of peat, to a grayish-white color highly suggestive of weathered quartzite. The structure is linear-parallel and is formed with extraordinary perfection. The gneiss is penetrated by dikes and more irregular intrusions of diorite which are probably related as to age and origin with the trappean mass of Tub Island.

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[1] O. M. Lieber, Rep. U. S. Coast and Geodetic Survey, 1860, p. 402.

[2] A. S. Packard, Jr., The Labrador Coast, 1891, p. 286.

[3] R. Bell, Scot. Geog. Mag. 1895, Vol. XI., p. 349.

Nowhere on this coast are trap-dikes so massive or so influential in determining the topographic form of the country, as in the region about Ice Tickle on the north side of Hamilton Inlet. Rodney Mundy Island and Ice Tickle Island are each about three parts composed of medium to coarse grained hornblende granitite, granitoid gneiss and fine-grained gneisses. The remaining surface is occupied by a multitude of great dikes, thick sheets, pods, or stock-like bodies of diabase which, on account of their black color, contrast very strongly with the other crystallines round about. The trap wherever examined is plainly intrusive. No vesicular structure was to be found. Both contacts of a typical pod showed the chilled and porphyritic zone characteristic of intrusion. A fine example of the dikes is seen on the ridge at Indian Harbor. It has parallel walls, is some two hundred feet in width, and is visible as a steep black wall a quarter of a mile along the Tickle. Very commonly the dikes are seen to swell out into thick trap-bodies three hundred to one thousand feet in diameter, and again, a stock will project through the gneisses without visible connection with the trap of the neighboring hills. The average strike of the intrusive masses is N. E.–S. W. The trap forms all the higher elevations, which thus assume the varying outlines of palisade, ridge, or dome, according to the shape of the intruded rock-body. Between them the schists and granites, on account of their inferior power to resist erosion, now underlie valleys that open seaward on the deep bays and tickles of a "drowned" coast-line. One will go far to discover so fine an example among wholly crystalline rocks, of such control over land-forms — the control of differential resistance to weathering.

The same association of gneiss-valleys and trap-hills extends at least ten miles to the westward of Ice Tickle. At Sloop Harbor, though still plentiful, the dikes (here hornblende biotite diorite with accessory augite) are too narrow to produce a great effect on the topography. Webeck Island, a soilless, driftless, because wave-swept, granitic swell a half-mile or more in length, affords a splendid exhibition of twenty-two huge dikes cutting across the island in parallel fashion. On the mainland, opposite Jigger Island near Webeck Island, an interesting group of dikes in granitite was studied. One of these is a handsome biotite diorite porphyrite; the other, a slightly porphyritic alkaline rock, with phenocrysts of microcline and a groundmass composed of microcline and quartz in micropegmatitic intergrowth and an amphibole with the characters of riebeckite.

Massive granitic rocks were found at each anchorage between Hamilton Inlet and Hopedale. At Sloop Harbor the hills are composed chiefly of a coarse hornblende granite; Jigger Island exhibits granitites similar to that of the mainland; thirty miles farther north, on the mainland opposite Conical Island, a flow-breccia of granitite cutting diorite proved to be extensive. Associated with similar rocks are the only sedimentary formations that were seen to the southward of Hopedale.

Sedimentary rocks at Pomiadluk Point. — Pomiadluk Point forms the extremity of a bold peninsula which projects northeastwardly from the mainland in about 55° N. Lat. Stretching along the southeast side of the peninsula for a distance of some five miles, is a broad bench from two to three hundred feet in height and from one and a half to two miles in breadth. On the southeast the bench falls into the sea quite abruptly; on the northwest it ceases at the foot of a steep ridge of granitite that composes the main part of the peninsula. Barometric readings on two different days accorded well in giving eleven hundred feet as the elevation of a prominent summit of the ridge. Its average height is not less than one thousand feet; toward Cape Strawberry it rises to twelve hundred feet, and is thus the highest land encountered on the coast between the Cape and the straits of Belle Isle.

The glaciated ledges of the flat though hummocky bench have been wave-swept during postglacial submergence and thus one can study the rock-composition and structure with exceptional ease. The bench is conterminous with a well exposed mass of metamorphic conglomerate. Along four cross-sections about a half a mile apart, the sedimentary band was proved to be very homogeneous. In a silicious matrix, often highly schistose, pebbles and boulders up to one or more feet in diameter are embedded. They are composed of granitite, quartzite, vein quartz, granite porphyry and metamorphic sandstone. They are almost always considerably flattened, though the granitite pebbles have oftentimes so far resisted the shear as to present still well-rounded outlines. The schistose structure strikes steadily N. 15° W.; its dip is variable but steep and generally to the westward. Not allowing for duplication, the thickness of exposed conglomerate measured on this secondary structure-plane was estimated at eight thousand feet. On the west the conglomerate becomes finer-grained and for a distance of three hundred feet from the granitite contact, is replaced by a band of metamorphic sandstone. The structural features are here identical with those of the conglomerate. Part of the cement of both rocks is made up of epidote, which colors the rock an intense green, especially marked where myriads of epidote crystals have formed along the joint-planes.

The limited time at our disposal, the extensive covering of elevated beach deposits and of land-wash at the inner edge of the bench, and, in an important degree, the disturbing influence of clouds of mosquitoes, prevented the discovery of the actual contact between sandstones and granitite. The granitite-pebbles in the conglomerate are very similar in character to the rock of the great ridge and suggest that they were derived from it. The deformation of the conglomerate is represented in the granitite by the appearance, especially near the contact, of a schistose structure, with a trend common to that of the conglomerate; the two rocks have evidently been squeezed together.

A sharp lookout was kept for fossiliferous bands, but no organic remains were discovered. Thus no conclusion could be made as to the age of the sediments. They have a close superficial resemblance to the Archaean metamorphic conglomerate series of Finland which the writer had already seen in the field. These Labrador sediments are cut by diorite, granite porphyry and diabase dikes and by many pegmatite and quartz veins.

Sedimentary rocks in Aillik Bay. — Aillik Bay opens at a point about fifteen miles northwest of Pomiadluk Point. It is a picturesque inlet some five miles in length and three-quarters of a mile in width. Its axis is directed north and south. The bay is rimmed about with massive rocks; diorites cut by granite porphyry dikes on the west; diorite intrusive into amphibolites and hornblende granite on the south; and coarse hornblende granite on the east. These various rocks compose high encircling ridges; at the base of these a narrow and interrupted belt of variegated banded quartzites outcrops on all sides of the bay. On the west, to north and south of our anchorage at Summer Cove, the quartzites could be traced at least two miles along the shore, but they were never found more than about one hundred yards from the beach. The white, red, and purplish layers often exhibited the cross-bedding of a typical sandstone. The strike of the beds is variable, changing from N. 60° W. to N. 20° W., the dips remaining low and constantly directed toward the land. The total thickness of the beds exposed was measured at one hundred feet. The belt terminates at the mouth of the bay in a veritable museum of rock-types, the quartzites being cut by an interlacing network of granitic and trap dikes as well as by pegmatitic, aplitic and quartz veins. On the east side of the bay opposite Summer Cove, similar quartzites dipping 50° S. 70° E. occupy a second belt along the shore of about the same dimensions as those of the western shore-belt, excepting that the sediments are here exposed for only three hundred yards. At either end the belt is cut off by hornblende granite and hornblende gneiss on which the quartzite seems to have been deposited. All these rocks are cut by numerous wide and conspicuous dikes of augite porphyrite and squeezed amphibolitic trap. At the head of the bay, quartzites dipping 55° S. 35° W. were seen on a low spur projecting into a boulder-covered tidal flat.

In this case, as at Pomiadluk Point, diligent search failed to disclose fossiliferous evidence as to the horizon of the stratified deposits; at both localities there is the same general relation between eruptives and sediments, suggesting that the latter are, roughly at least, contemporaneous deposits.

Threading the maze of islands extending from Aillik Bay to Hopedale, no halt was made and no sampling of the coast geology could be carried on. From the somewhat monotonous character of the island-zone both as to color and form, it seemed to be composed of the coarse biotite gneiss which characterizes the rugged hills about Hopedale. Trap dikes were always in the view. Striped Island, twenty miles E. S. E. of Hopedale, owes its name to the curious contouring habit of twelve great dikes that have penetrated the granitic boss-like island along a nearly horizontal system of master-joints. They are now visible all around the clean-swept island but are particularly conspicuous on the west side for a distance of a half mile. At Hopedale, the wonderfully contorted gneiss, which is penetrated by numerous diabase dikes, has an average strike of N. 55° W. Thence northward, the archipelago of ragged sub-conical islands of the same gneissic composition extends with northwest trends to Ford Harbor on the east end of Paul's Island. Anchoring at Quirk Tickle, fifty miles north of Hopedale, we found the banded biotite gneiss with northwest strike and indistinguishable from the rock at Hopedale. Extending as it does a distance of at least one hundred and twenty miles along the coast, the Hopedale gneiss is one of the most important members of the whole crystalline complex.

The Nain gabbros. — The Hopedale gneiss underlies the eastern end of Paul's Island, but a few miles west of Ford Harbor, it comes in contact with the famous anorthosite and allied gabbro whence is derived the schillerizing labradorite. (Plate **11**). One may collect specimens of the feldspar from the numerous erratic boulders sprinkled over the hills about the harbor. The direction of glacial striation shows that these must have been carried to their present resting-places from the west and southwest. It was likewise made clear to us on the northward journey that the gabbro must be in great development in order to furnish such an immense amount of erratic material as we saw. Skirting the north shore of Paul's Island, the "Brave" was headed for Nain, passing through a long tickle walled in on either side by high cliffs of massive gabbro for fifteen miles before the mission station was reached. At the station we were still about twelve miles from a quarry where "precious" labradorite in place has been opened by Mr. R. G. Taber. The desire to see the mineral in place decided us to risk the schooner among the dangerous channels of the island-labyrinth. At Nain, however, we had the good fortune to find Dr. Wilfred Grenfell, superintendent of the Deep-sea Mission, then in command of his fine new steamer, the "Strathcona." With great kindness he invited our party to accompany him on the steamer to Mr. Taber's quarry; we thus spent one of the most enjoyable days of the summer in the accomplishment of what would have taken the schooner, by reason of the calms and baffling winds then prevailing, two or three days to effect. The quarry is situated on the southwest side of a small island called by the Eskimo, "Napoktulagatsuk." It lies within one fourth of a mile from the mainland.

Napoktulagatsuk is elliptical in shape and has a major axis of about six hundred yards. The opening has been made in a steep glaciated slope and covers an area of about twenty-five hundred square feet. At the foot of the slope a thirty-foot raised beach bears a ruined derrick, and a tramway which showed by their dilapidation that work has been discontinued for some years. While the whole island is composed of anorthosite, the schillerizing feldspar occurs only in the form of isolated patches up to fifty feet in diameter. These are generally, though not always, coarser in grain than the surrounding rock, and are pegmatitic in look. In the sunlight, the fresh surface of the rock presents a rich and beautiful appearance. The dominant color is the familiar blue, but it is associated with vivid green, bronze, orange, and red phases. These pocket-like schillerizing masses are clearly contemporaneous with their country-rock. Both types are characterized by the well-known composition of this gabbro. Both are cut by aplitic dikes and pegmatite veins.

The lofty dome-shaped islands situated between Nain and Napoktulagatsuk as well as all the mainland visible thereabouts are composed of the gabbro. There is every probability that the schillerizing phases may be found sporadically throughout this great area. They are known to occur on the eight hundred-foot Mt. Pikey, southwest of Ford Harbor. Peculiarly sombre in hue, profoundly glaciated and almost entirely devoid of vegetation, these great hummocks afford a scene of complete desolation almost without parallel even on the barren coast of Labrador.

Gneisses similar to those at Hopedale compose the outer islands north of Ford Harbor, but it is probable that the Nain gabbro is continuous with another great area that we first met with on Newark Island, and afterwards found extensively developed on the mainland at Port Manvers. At Black Island Harbor the gabbro is coarse; at Port Manvers it is finer-grained. In both cases the composition is identical with that characteristic of the Nain occurrence. The rock of this northern area has the habit of concentric weathering, boulders of disintegration forming great cyclopean walls on the glaciated ledges at Port Manvers. The rock seems to be much less resistant to the weather than the gneisses. The floors of glaciated valleys in the gabbro are invariably occupied with screes of the crumbling rock. A truly imposing example is seen in the long sweeping curve of waste that covers the lower fifteen hundred feet of the northern face of Mt. Thoresby.

The Kiglapait.

Fifteen miles north of Port Manvers the eastern end of the Kiglapait springs directly out of the sea. The name of this mountain-group is an Eskimo word meaning "The Great Sierra" and refers to the very ragged sky-line and general outlines. The axis of the range runs due east and west, parallel to the coast-line which here has an exceptional trend. The sierra is not more than thirty miles in length, but, on account of its conspicuous position on the shore, is strikingly picturesque. Ten distinct and individual summits from two thousand five hundred to four thousand feet in height could be counted from the schooner. No one of these, so far as the writer has been able to determine from missionaries, fishermen, or from the literature, has as yet received a name. Here, as in the higher mountains of the north, there is abundant opportunity for systematic field-work on the part of such an organization as the Appalachian Mountain Club.

We had hoped to spend some days, if not weeks, in the study of these interesting mountains, but the lateness of the season forbade our dropping anchor within reach of the noble range. Judging again simply from the peculiarly dark color of the bare rock-surfaces, it seems probable that the gabbro seen at Port Manvers makes up most of the Kiglapait, which will thus represent the Coolin type of gabbro mountains in Scotland.[1]

On the other hand, it was discovered that banded and much contorted gneisses compose the numerous low islands lying between Ford Harbor and Mugford Tickle, a distance of fifty miles. At the Tickle, the undulating platform of the complex disappears beneath the quite different formations of the Kaumajets.

THE KAUMAJET MOUNTAIN GROUP.

For a distance of fifty miles to the southward we had marked the majestic pile of the Bishop's Mitre with the associated mountains of the mainland. Their summits were at the time covered with a fresh fall of snow; the brilliancy of the crests recalled the etymology of the name which again illustrates the Eskimo's feeling for natural scenery. "Kaumajet" signifies "shining"; the range is the Himalaya of Labrador.

As indicated by its position, composition, and topographic character, the island of Ogua'lik really forms the southern extremity of the Kaumajets. Mugford Tickle separates it from the mainland. It was in this narrow channel that our anchorage was chosen. Again we had occasion to mourn the slowness of our northward progress, for it would have been of the highest interest to devote a fortnight at least to the exploration of this region; in order to be certain of reaching Nachvak, however, we allowed but two days in which to secure information concerning the nature of the massifs immediately surrounding the vessel.

The nine-hundred-foot scarps of Ogua'lik would have been impressive among the tamer landscapes of southern Labrador, but they were dwarfed beside the mighty walls of the opposing mountains only a mile or two distant. We had entered the tickle late at night, and in the brilliant starlight had discerned the huge piles looming up in solemn and formless grandeur. Their mystery became in part dispelled as a bright sun disclosed a scene in its way unrivalled in Labrador. Due north in the centre of the view two gracefully rounded knobs, estimated, by the aid of barometric readings half-way to their summits, to be two thousand five hundred feet in height, lay close to the verge of an almost vertical precipice from one thousand to one thousand two hundred feet high. Below this a series of lesser cliffs, separated by steeply sloping screes of rock-waste stepped downward to the uneven floor of a deep N. E.–S. W. valley. On the southeast the valley is bounded by a similar arrangement of cliffs and taluses. It ends as a great cul-de-sac two miles in length in a thousand-foot head-wall over which there cascades a large brook.

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[1] A. Geikie, Scenery of Scotland. Ed. 2, 1887, p. 215.

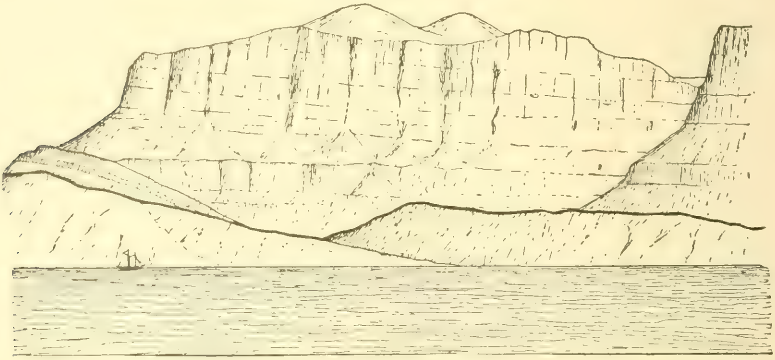

FIGURE 1.— Dissected plateau of Mugford sedimentary series, viewed from Mugford Tickle. Each of the two summit knobs was estimated to be about 2500 feet in elevation. Looking north. Drawn from a photograph. Heavy black line represents upper surface of the basement Complex.

On landing, we found that the first and natural impression, that this systematic array of scarps and taluses signified a stratified structure for the massif, was justified (Fig. 1 and Plate **11**). At the foot of the great slope the basement of all the other rocks is represented in an irregular floor of contorted and faulted gneisses and amphibolites. The surface of the familiar complex appears at all elevations above the sea up to about six hundred feet. Next above the light colored zone of the schists comes a series of black slates fifty to one hundred feet thick, indurated at the contact by a conformable three hundred-foot sheet of apparently intrusive diabase. The edge of this sheet forms one of the lowest strong cliffs above the basement. The diabase in its turn is overlain by a great thickness of slates, quartzites, sandstones, quartz breccias, volcanic agglomerates, and trap layers. The inaccessibility of the cliffs and the shortness of the time allowed for examination rendered it impossible to determine the absolute strength of the various members. The enormous size and number of the blocks found in the screes seemed to show that the greater part of the thousand-foot cliff is made up, as they are, of a volcanic breccia. The basalt agglomerate, which is also a significant part of the stratified series, is typical and encloses numerous bombs with bread-crust structure.

These sediments and intercalated traps everywhere have low dips; therein we have an explanation of the plateau-like character of the relief, as dissimilar to any other on the coast, as the residuals of Torridonian sandstone are unlike the rolls of gneiss in the Scottish Highlands. Combining the observations made in the gorge below the waterfall, with those made in the Tickle and outside to the southeast of the Bishop's Mitre, the structure of the rocks on the northwest side of the Tickle is that of a flat syncline with a N. W.–S.E. axis, crossed, west of the waterfall, by a transverse warp. On the southwest, the effect is that of an eroded low half-dome. The steepest dips occur near the middle of the Tickle, where a magnificent section of the whole stratified series can be easily studied as the beds plunge into the deep water (Plate 1). The total thickness of the stratified series is about twenty-five hundred feet.

On Ogua'lik at the southwest end of the Tickle, the gneisses are overlain by an intrusive sheet of diabase, about fifty feet in thickness, upon which are piled slates, quartzites, limestones, and sandstones with interbedded traps. Whether the latter are intrusive or extrusive we had not time to determine, but the apparently complete absence of vesicular structure and of other signs of volcanic activity would speak for the latter interpretation. The limestone is rather crystalline, and is strongly charged with pyrite. A shallow opening and a few rusty tools showed that attempts had been made to test the rock for either gold or copper.

The whole of Ogua'lik corresponds in composition with these cliffs of the northwestern shore of the island. At the eastern end, black cliffs, fifteen hundred feet in height, form the edges of a capping massive sheet of trap estimated at seven hundred feet in thickness, overlying some nine hundred feet of sediments again unconformable on the gneissic complex. While there exists a general similarity between the formations on either side of Mugford Tickle, their failure to match on opposite sides of the strait seems to imply a fault coincident with it in direction.

The unconformity of the crystalline basement and the sediments is extremely well shown at both ends of the Tickle, especially at Cape Mugford itself (Plate 2). The gneisses have participated in the folding of the sedimentary cover; it is owing to that fact that they disappear in the middle cliffs of the strait. The surface of unconformity would, if produced, rise to seaward so as to pass completely over the fantastic peaks of Nanuktut Island. This island thus forms a strangely ragged outlier of the crystallines from which the sedimentary cover has been swept by denudation. The island has been called by the "Newfoundland Pilot" "the most remarkable and unmistakable land on the Labrador coast."[1] Nothing could exceed the contrast between its character and that of the Mugford massifs. The light gray precipitous two-thousand-foot peaks of the one oppose the black, tabular, greatly dissected piles of the other.

At Cape Mugford, which forms a nearly vertical sea-cliff about two thousand feet in height, we were struck with the highly ferruginous character of the sediments, broad bands of variously tinted iron-rust enriching and enlivening the color effects in a marked degree. Numerous waterfalls and extensive banks of snow lent welcome relief to the dark cliffs, the black recesses of huge sea-chasms, and the savage gorge-like inlets that opened one after another as our schooner slowly forged through the "tide" around the cape.

Fine as this scenery was, still greater magnificence awaited us as we came face to face with the Bishop's Mitre toward the close of a memorable day of sailing. Seen from the northeast, the mountain, estimated to be considerably more than three thousand feet in height, displays a symmetry which is most remarkable in view of the fact that the present profiles are everywhere the result of erosion. As the name implies, there are two peaked summits. They are separated by a sharp notch about five hundred feet in depth. This breach is but the uppermost part of a gigantic ravine that cleaves the mountain to its base at the shore more than two miles from the notch. Occupying the bottom of the ravine an uninterrupted snow-bank still marked, in the month of August, the line of symmetry of the whole mountain. From either peak of the Mitre a rugged razor-back ridge descends, each gradually diverging from the other across the widening intervening trench. With essentially equivalent transverse and longitudinal profiles, the two spurs further match as each terminates at an elevation of about one thousand feet, in a bold rock-tower. Each tower rises eight hundred feet or thereabouts above the ridge-crest and, on the east, drops suddenly the full eighteen hundred feet into the sea. The matching of the right and left halves of the mountain does not stop with the form. Each of the sentinel towers is composed above of black Mugford sediments reposing on five hundred feet of the light gray gneissic complex. The architectural quality of these great buttresses and of the Mitre itself is greatly enhanced when a fresh fall of snow brings out the nearly horizontal structure of the whole massif and is such as to make one believe that the Mitre is the most beautiful single mountain on the coast.

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[1] Newfoundland and Labrador Pilot (ed. 3, Hydrog. Office, London, 1897, p. 680).

About four miles to the westward of the Mitre is the summit of the highest mountain in the Mugford region; it was estimated to be in the vicinity of four thousand feet in elevation. A cone of simple yet effective outline, it is easily recognizable from a ship for a distance of seventy-five miles either north or south of Cape Mugford. So conspicuous is it that one cannot but wonder how it has been left so long neglected and left unnamed among the landmarks of the Admiralty charts. On board our own craft we fell into the habit of calling the peak "Brave Mountain," after the name of our doughty little schooner.

Pursuing our northward way tolerably close to land, it could be seen that for at least fifteen miles from Cape Mugford, the heavy sedimentary cover and its crystalline cover continued. Not the least important element in the imposing panorama was the "Finger Hill" of the charts, a long narrow plateau, perhaps two thousand feet in height, that stands close to the shore, and is evidently composed of the Mugford sediments. Its name is derived from a large number of tors or rock-pinnacles resulting from the dissection of the edges of nearly horizontal strata. Beyond Finger Hill, the coast turns sharply to the westward, and we could see no more of the Kaumajet. It is known that this range extends to the west and northwest of Cape Mugford, and it is presumably of sedimentary or volcanic origin over most of its extent. No fossils were found in any part of the Mugford series. Here, as in the Kiglapait, exploration is urgently needed.

From Finger Hill to Hebron we saw but little of the land. Going north, the "Brave" traversed this section of the coast during the night; returning, she remained at an average distance of five miles or more from the shore. Mainland and islands are relatively low, altitudes of one thousand or fifteen hundred feet being rarely surpassed. It was clear from the color of the rocks that the Mugford series does not compose this stretch of country; it is highly probable that it belongs entirely to the gneissic complex.

THE TORNGAT MOUNTAIN RANGE.

TOPOGRAPHY. — The triangular peninsula east of Ungava Bay is composed of two distinct topographic belts. On the west and southwest the land is caribou country, low, flat, grass- or moss-covered, with a considerable amount of stunted timber growing upon it. Rising abruptly out of this little elevated belt (charted as the "Kangiva") is the long, serrate chain of mountains, or strongly-dissected mountain plateau, extending one hundred and fifty miles north-northwest from Kangerdluksoak to Cape Chidley. In the southern part, the range has an average width of about fifty miles, but it narrows in the north. On the east, it is bordered throughout its extent by the Atlantic. Tectonically, the chain is closely related to the entire gneissic border of eastern Labrador, but its superior elevation and peculiar topography early marked it out as an orographic individual. Owing to the wild, forbidding, and awe-inspiring aspect of the mountain-wall, it is called by the Eskimo the home of the "Torngat," or "bad spirits."[1] Kohlmeister and Kmoch mention the name "Torngets" for the N. W. extremity of the ranges,[2] which was mapped as such by Weiz.[3] So far as the writer has been able to discover, the only other name for any part of the system is that given to the east-central portion, the "Nachwak Mountains" of Steinhauer,[4] or "Nachvak Mountains" of Kohlmeister and Kmoch.[5] There seems to be no good reason for regarding the whole highland belt as other than a structural and orographic unit. It is therefore proposed that the ancient name "Torngat" be extended so as to include all the belt from Hebron to Cape Chidley.

For a summary of what little is known concerning the Torngats, the reader is referred to "The Labrador Coast" of Packard.[6] Lieber, Bell, and Koch have respectively made local studies at Eclipse Harbor, Nachvak, and Ramah; all agree in emphasizing the wild, ragged, alpine nature of the relief. From end to end of the range, razor-back ridges and horns abound. These are separated by lower rounded hills and yet more conspicuously by numerous deep fiords and glaciated valleys or glens, the near relatives of the fiords. All three observers came to the conclusion that an alpine character has been preserved from preglacial times because the continental ice-cap did not cover the Torngats. Bell placed the average elevation of the local valley-glaciers of the ice-period at about two thousand feet above the present sealevel. As noted more fully below, this summer's observations correspond very closely with his estimates. It would be a mistake, however, to attribute a glacial origin to the rounded profiles of many of the dome-shaped mountains that alternate with the horns. The former are to be regarded as the result of atmospheric erosion and their slopes as the graded surfaces of mountains normally subdued to relatively tame form by that agency. The same stage of development awaits their more acuminate neighbors. Glacial erosion has thus not only not reduced the higher summits to flowing outlines; by reason of the fact that glaciation has been confined to the valleys, it has even greatly steepened many slopes and given a more rugged aspect to the landscapes than belonged to them in preglacial times. One must ascribe a good share of the wild picturesqueness of the range to its profound trenching by valley-glaciers. During the glacial period, the Torngats seem to have formed a great dam facing the central névé of Labrador which thus lay on the Kangiva side. It was only here and there that ice-tongues crept over the low transverse passes, overflowed into the larger longitudinal valleys, and reached the Atlantic through the corresponding valleys on the east. At that time, the range appeared in the form of a large number of gigantic nunataks projecting from one to perhaps five thousand feet above the ice. There resulted among the salient features of the mountain-belt, the long east and west fiords, of which Nachvak Bay is doubtless the finest example.

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[1] Translation due to Rev. A. Stecker.

[2] Journal, 1814, p. 50.

[3] A. S. Packard, The Labrador Coast, p. 226.

[4] H. Steinhauer, Trans. Geol. Soc. London, 1773, vol. 2, p. 488.

[5] Journal, p. 20.

[6] Pp. 3, 6, 19, 226.

THE GEOLOGY. — Crystalline schists form the principal constituents of the range. Near Hebron, the Johannesberg (2200 feet) is the loftiest of the high points which begin the chain on the south. At this mission station, the rocks were examined and found to be common biotite gneiss and amphibolites, intersected by trap dikes. The schists here trend due northwest, fairly conforming in attitude with the general trend of the southern Torngats. Bear Island, a half dozen miles to the eastward, exhibits a splendid exposure of the dikes. Similar, though much larger, ones can be traced on the cliffs all the way to Nachvak, a distance of seventy miles. They are usually vertical, often as much as three hundred feet in breadth and always in contrast with the schists into which they have been intruded. They are particularly developed on the flanks of Mt. Blow-me-down (*ca.* 3500 feet). The continued prevalence of these intrusives along the coast for the seven hundred miles from the Straits is, indeed, one of the most notable phenomena of its geology.

The Ramah Sedimentary Series. — The enterprise of Prof. Delabarre and Mr. Adams permits of the introduction at this place of some interesting data regarding a very extensive stratified cover which appears to bear the same relation to the crystalline complex as that of the Mugford sediments. They left the schooner at Hebron and walked over the mountains a distance of one hundred miles to the Hudson's Bay Post in Nachvak Bay, where they boarded the vessel again. They crossed the peninsula between Kangerdluksoak and Saeglek Bay and were carried by Eskimos across the latter inlet from the Paugnertok (see Weiz's map in Packard's "The Labrador Coast, p. 226). Thence they walked to Ramah Bay, were most hospitably received by the missionaries and after a much needed rest, went once more overland to their destination. They report that until they had reached a point three or four miles north of Saeglek Bay (at about 64° W. Long.), they passed over gneisses similar to those seen at Hebron. Then bands of black slate alternating with quartzite were met with. Soon continuous slates with interbedded sandstones and quartz breccias were crossed, and these persisted to a point some four miles north of Ramah Bay. Thence the route carried them over schists equivalent in character to those found on both sides of Nachvak Bay. The sediments are highly indurated, and often somewhat metamorphosed. Neither the quartzites nor the greatly cleaved and pyritiferous slates yielded fossils to the travellers, who were constantly on the lookout for them. What seems to be a continuation of the same sedimentary terrane was seen by the writer, though at a distance, in the form of ragged black cliffs fifteen hundred feet or more in height, lying southwest of Gulch Cape. The massifs corresponding are tabular, with very low dips and are plainly stratified. Kohlmeister and Kmoch mention the Ramah slates in the narrative of their journey in 1811.

OBSERVATIONS IN AND ABOUT NACHVAK BAY. *Topography and Scenery.* — At dawn on August 21st, the "Brave" was lying-to about six miles from Gulch Cape waiting for daylight before the not particularly safe passage of the Nachvak Narrows could be attempted. As we drew nearer the shore, a brilliant sun flooded with light a scene most impressive to us who were fresh from the softened outlines of the southern coast and from the yet more featureless landscapes of southern New England. In front stood the bold fifteen hundred-foot headland whose many ravines have given the cape its name. Just west of it rose a curiously regular hill of about the same height, as typical a cone as one could well imagine, yet apparently an erosion form derived from the destruction of crystalline schists. To the right of the cone, a long east and west ridge, estimated at twenty-five hundred feet in height, claimed instant attention, as it represented, better than any part of the Torngats yet seen, that serrate topography which Bell and others have emphasized in the descriptions of the region. It is a knife-edged sierra, trenched on either flank and from top to bottom by a score of deep transverse ravines. In the background, visible through two U-shaped notches, appeared the stratified tables already referred to. Still farther to the north, the view included a lofty wall four miles long, interrupted by deep clefts and by one strong valley-notch. It ends abruptly at the Narrows of Nachvak Bay. About five hundred yards from the Narrows we lay some time becalmed close beside this cliff (the eastern slope of Karmârsuit), one of the grandest on the coast. It was estimated at approximately two thousand feet in altitude. With an angle of slope of about eighty degrees, with neither vegetation nor talus, it surpasses in its wild severity many more celebrated precipices of the world. About three miles northeast of the Narrows, a very perfect imitation of a volcanic cone was photographed and is here reproduced in Plate **5**. Estimates gave the upper lip of the "crater" a height of two thousand feet above the sea; the depression itself a depth of one thousand feet or thereabouts. The amphitheatre seems to be an unusually good specimen of the glacial cirques which we were to find in great numbers wherever we had a chance to view the Torngats. Lieber noticed the frequency of similar forms on Aulatsivik Island. Finally, on the extreme right of the view, some fifteen miles from Gulch Cape, the coast was outlined by a sierra, "Mt. Razorback" (4000 feet, est.), one of the most rugged and most alpine, though not among the loftiest, members of the mountain-system.

Among the maps of Nachvak Bay which have yet been published, that of Weiz[1] is the best. While on board the schooner or in the skiff used in sounding, the writer made a rough sketch of the inlet which is believed to represent still more closely its true form. (Plate **12**). For purposes of orientation, the Eskimo names for the more important landmarks have been inserted. These names we owe to Mr. George Ford, the Hudson's Bay agent at Nachvak, who, in this as in all other matters, was unwearied in affording us information about the country. The spelling of the names furnished by Rev. A. Stecker, originally in German, is phonetic after the sound of English vowels and consonants, and hence differs in a few instances from that adopted by Weiz.[2]

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[1] See Packard, "The Labrador Coast," p. 226.

[2] The following is a glossary of names appearing in the sketch-map of Nachvak Bay, with their translations by Rev. A. Stecker of the Moravian Society.

Idyutak, "lever," referring to the form of the mountain.

Ivitak, "red-colored," land with a reddish color; red ochre; bricks.

Kaputyat, "place for trout-spearing," or (better) "place for spearing."

Karmârsuit, "wall." Some lands in the shape of a wall are called "Karmârsuk" (little wall) or "Karmârsoak" (great wall). "Suit" is a plural suffix. [*over*]

It will be seen from the map that the width of the bay averages about one and a half miles. Its length is twenty-five miles when measured to the head of either of the two arms, the Tallek, or the Tessyuyak. Weiz's map exaggerates both dimensions considerably. It is important to note that the trench filled with the salt water of the bay is continued at the head of each arm by a wide and deep glaciated valley. That corresponding to the Tallek runs to the south, its floor rising slowly, until, at a distance of about twenty miles from the Bay, it terminates in a flat divide adjacent to the valleys drained into Nullatatok and Saeglek Bays. The upper end of the Tessyuyak has been dammed across by a splendid alluvial fan that is growing vigorously out from the mouth of a hanging valley, the floor of which stands about one hundred feet above sealevel on the south wall of the inlet. The result has been the formation of a fresh-water lake, the Tessersoak, three miles long, which is drained by a rapid stream slightly trenching the fan. Beyond the lake to the westward, the deep valley extends with but little abated strength as far as the eye can follow it when viewed from the top of the fan. Mr. Ford informed us that the valley leads directly across the Torngats to the flat country on the west. The total length of this whole valley is thus about forty-five miles; rather more than half its floor lies beneath the sea.

On both sides the bay is walled in by very precipitous cliffs varying in height but averaging nearly two thousand feet above the sealevel. The highest point immediately overlooking the water is unquestionably the summit of the Idyutak, where its western face dominates the Tallek (Plates **3** and **4**). Its height (3400 feet, bar.) was long since

Kipsimarvik, meaning unknown; old Eskimo word perhaps, of which the meaning is lost, as in the case of many names of places.

Kogârsuk, "small brook."

Korlortoâluk, "big water-fall."

Kutyautak, "wedge," referring to the shape of the mountain.

Nachvak, "found, found at last." The first Eskimo, coming from the west in search of the salt water, cried out "Nachvak" when he reached the head of the bay.

Naksâluk, "great valley."

Sennerkitte, "tributary, branch stream."

Sittorutsit, "mountain side where avalanches are common."

Tallek, "arm," referring to the shape of the bay.

Tessersoak (also Tesseksoak), "large pond."

Tessyuyak, "like a pond."

Tinutyarvik, a basin at the head of a cove, barred off by a continuous wall-like shoal, so that at low tide fish are trapped as in a weir.

measured by Captain Bolton of the British Navy. On the opposite side of the Tallek is the slightly lower but equally majestic Kutyautak. The twenty-five-hundred-foot cliffs of the latter have slopes of from fifty to eighty degrees. Yet more imposing, perhaps, are the extremely rugged cliffs of the Tessyuyak near its head. They were estimated at twenty-five hundred feet in height on both shores. Their striking character is due not only to altitude and the narrowness of the bay, here but a half mile in width, but also to the greatly variegated color of the rocks. The usual neutral tones of the cliffs in the Torngats is exchanged for an irregular association of browns, reds, greens, yellows, slaty blue, grays and even white, according to the nature and condition of the schists or of the products of efflorescence.

While the fiord walls, varying thus from fifteen hundred to thirty-four hundred feet in height, are relatively continuous and enclose a well-defined trench, their sky-lines are often broken down by lateral notches. Some of them belong to glaciated valleys, the bed-rock floors of which lie below sealevel. Such inlets are more or less filled with deltas and alluvial fans built out by rapid brooks and torrents. Still more numerous are side-valleys that characteristically mouth at varying heights above the fiord waters. From Kipsimarvik (the Hudson's Bay Post) to the Narrows, twenty-two well developed cirques or corries from three to eight hundred yards in length were counted. The small streams draining them leave the corries at altitudes varying from one to two thousand feet above the sea. Identical in form and relations with the amphitheatres lining the larger glaciated valleys of the Alps, of Norway, of Scotland, and of the Rocky Mountains, they may best be explained as the result of very local but intense erosion of small ice-tributaries feeding the now vanished main glacier that once occupied Nachvak Bay. (*cf.* Plate **5**.) Other "hanging valleys" of much greater dimensions are likewise found. The most important of these is drained by the large stream furnishing most of the water in the picturesque cascade "Korlortoâluk," two miles east of Kipsimarvik (Plate **6**). The main leap of this fall was found by barometric means to be three hundred and seventy-five feet high; the total height of cascading water visible from the bay is five hundred and twenty-five feet, but the valley floor really appears at a height of seven hundred and fifty feet above the sea. The fiord is five hundred feet deep opposite the waterfall. There is thus a total discordance of twelve hundred and fifty feet in the altitude of the main and lateral valley floors. On an estimated gradient of two hundred feet to the mile, the lateral valley turns north-

northeast and thus runs nearly parallel to the Bay. The valley terminates, at a distance of eight or ten miles from the cascade, in a number of deep corries. Unlike the fiord, the lateral valley flares broadly and its floor is occupied by a half dozen lakes large and small. It is itself provided with two branch-valleys which join it just above the cascade. One of them ends in a glaciated col, the other in a magnificent cirque a mile in diameter. The drainage of these three valleys serves to sustain the waterfall all the year round.

It may also be noted that a fine series of cirques and hanging valleys look over the Kogârsuk. The most notable of these is the one whose drainage, forming the Sennerkitte brook, cascades more than two hundred feet into the Kogârsuk. It lies north of Mt. Ford, runs five miles or more to the eastward, and is floored over with a number of small lakes. (Plate **12**.)

An early statement of an explanation for these apparently abnormal valleys was given by Helland: "If a glacier fills a tributary valley, and is thinner than that in the main valley, the depth to which it erodes its bed must be less than the depth of the main valley. Hence many tributary valleys must debouch high above the bottom of the main valley. Instances abound of tributary valleys debouching thousands of feet above the beds of the main valleys along the steep sides of the fjords of western Norway."[1] Helland does not seem to have recognized the full significance of his idea in the general theory of glacial erosion; perhaps because he was so fully persuaded at the time of the competency of glaciers in this regard, that further emphasis was not necessary. The advantage of living on the ground may here have aided perception just as the ancient belief of the Swiss peasants long antedated the theory of Charpentier and Agassiz that the Swiss glaciers were once much greater than now. Davis, Gilbert, and Penck have recently and independently developed the idea to something like its full importance. Reference may be made to the detailed memoir of Davis for fuller information on this subject.[2]

Soundings showed that Nachvak Bay is an excellent type of fiord. Twenty-one casts of the lead sufficed to determine the submarine relief in its main features. (Plate **12**.) The greatest depth, of one hundred and ten fathoms, was found at a station six miles from the Narrows, where the water is nearly as deep. Two miles to seaward of the Narrows, the bottom shoals to an interrupted rock-sill which forms a long line of breakers athwart the bay entrance. Ships generally enter the bay by a broad channel running from Gulch Cape close against the shore. The sill appears to be represented on its bottom where a sounding gave twenty-five fathoms of water. The sill thus rims about the mouth of the bay in a gentle curve. To the eastward the Admiralty charts indicate considerably shallower water than that in the bay itself. Up to a distance of twelve miles from the Narrows, the average depth of the bay is one hundred fathoms; then the bottom rises rapidly to a narrow bar running across the inlet. Upon it the maximum depth obtained was eighteen fathoms. The bar ends at either shore in a projecting spur of bed-rock; a fact that seemed to indicate that we have here to do with a rock-sill. Eight miles further west, a very similar sill crosses the bay, with a maximum depth of fifteen fathoms. To east and west of this bar, eighty and sixty-eight fathoms respectively were found. This coincidence in location of sills with constrictions in the fiord seems to be exceptional among the features of this type of inlet. A longitudinal profile of the bottom is given in Figure 2. The broadly U-shaped transverse profile of the Tallek is probably of the same general quality as the average cross-section of the whole fiord.

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[1] A. Helland, Quar. Jour. Geol. Soc., 1877, Vol. 33, p. 174.

[2] W. M. Davis, Proc. Bos. Nat. Hist., 1900, Vol. 29, p. 273.

The extremely rapid destruction of the fiord walls, rendered so steep by glacial "over-deepening" has entailed the growth of abundant talus, and thereby the declivity of the submerged slopes has been diminished. This filling of the trench is particularly noticeable at the base of the numerous alluvial cones and fans which almost invariably appear where strong lateral ravines notch the cliffs. Creeping and leaping of the glacial drift down the slopes is going on apace. Large scallops or tongues of streaming clay,

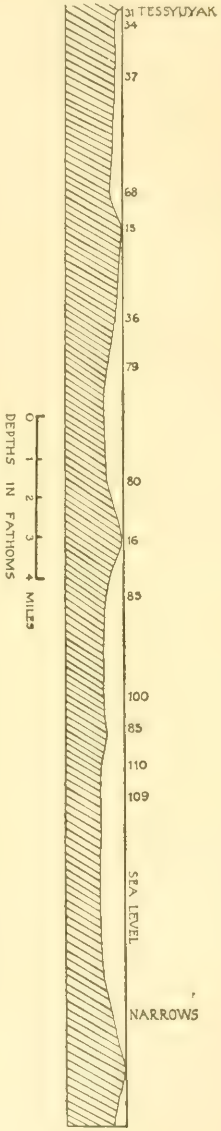

FIGURE 2. — Longitudinal section of Nachvak Bay.

gravel, and small boulders abound. Mr. Ford states that, after a heavy snowstorm, as many as twenty or thirty avalanches may, in the succeeding twenty-four hours be expected to fall within sight or sound of the Post. These slides always bring a greater or less amount of loose rock with them which, in winter, will find a temporary resting place on the frozen surface of the fiord, and gradually build a fringe of débris resting on the ice parallel to the shores. As might be expected, the number of these falls is greater in the spring than at any other time of the year. The marks made by the bounding boulders where they strike soft ground were found to be in the month of August, extremely fresh, and must have been formed only a few days previously. Mr. Palmer saw one boulder six feet in diameter fall from the wall of the Tallek, and, after its last rebound, leap fully a thousand feet before it struck the surface of the water. As in the Alps, there is a certain element of danger in travelling on these slopes.

It is not to the credit of American geographical enterprise that the Torngats are to-day unnamed, unmeasured, unknown in any scientific sense; yet they doubtless represent the highest land on the mainland of the American Atlantic seaboard from Hudson's Strait to Cape Horn. Lieber stated that "they are not less than 6,000 feet high, and some peaks may be 10,000 feet high." Koch later remarked that "the highest points of this range are opposite the island of Aulatsivik, and reach elevations of from 8,000 to 9,000 feet."[1]

One short fortnight was quite insufficient to permit of any exhaustive work on the determination of altitudes, especially as there were other and more important problems which engaged our attention while the "Brave" lay anchored at Kipsimarvik. Partly for this reason, only a few of the lower and nearer mountains were ascended. (Plate **12**.)

Immediately back of the Hudson's Bay Post, on the northeast, a rounded knob was found, with the aid of two standard compensated aneroids, to be twenty-eight hundred feet above high water. It was called by our party "Mt. Elizabeth," after the young daughter of the Hudson's Bay agent. This mountain is separated by a profound notch from "Mt. Ford," named after the agent himself. It lies still farther to the northeastward; its altitude, determined again by the barometers, is thirty-nine hundred feet. From the summit a superb panorama is obtained on all sides. Due north, two conspicuous peaks some four miles distant across a deep east-west valley, cut off some of the view. The westernmost was ascended by Professor Delabarre and Mr. Adams and determined at forty-four hundred feet in height. This peak is, so far as known, the highest yet measured in Labrador. The other peak was not climbed, but was estimated by these gentlemen to be fifty-three hundred feet in height. Still higher summits dominate these on both sides of Nachvak Bay. From Mt. Ford the writer saw two extremely sharp horns, bearing N. 25° W. These must have been at least forty miles distant, and in all probability are members of the group of the "Four Peaks" mapped on the Admiralty chart as southwest of Eclipse Harbor. Judging from their conspicuous position in the sea of mountains, each of them must be at least seven thousand five hundred feet high. South of Nachvak Bay there are several fine peaks more than six thousand feet in altitude.

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[1] Quoted by Packard, "The Labrador Coast," p. 228.

The Geology. — Bell has already given us some notes on the nature of the rocks in the bay. Additional observations made last summer could evidently not form a very complete or systematic piece of work. The Torngats, where examined along the long cross-section of the bay, are seen to be essentially composed of contorted but generally highly inclined crystalline schists, chiefly gneisses. The average strike is N. 25° W. At Skynner's Cove (Plate **12**) ledges of common gray biotite gneiss and dark-colored hornblende gneiss striking N. 5° W. are covered with many large boulders of an arkose-like rock enclosing roundish, often large, grains of opalescent quartz. This rock was not seen in place ; it may be related to a well-stratified, light colored rock series that occurs on the opposite side of the bay. The latter series is about five hundred feet in thickness, is manifestly sedimentary and lies unconformably upon the gneisses. Unfortunately there was no opportunity to make a landing and investigate the region closely. It may be that the cover represents a continuation of the stratified rocks seen southwest and west of Gulch Cape. The rocks of the Nachvak cliffs were sampled by Bell, who reported to have found there a slaty breccia apparently similar to the arkose of Skynner's Cove, and, as well, a "fine-grained silicious schist."[1]

Nine miles west of Skynner's Cove, on the north side of the bay, the well-banded gneisses still strike N. 5° W. ; they are here cut by a remarkable network of dikes exposed on a sheer fifteen hundred-foot cliff. The parallelism of the dikes gave them at first sight the look of sills, but closer examination showed that they are independent of the schistosity of the gneisses.

Near the Hudson's Bay Post, the rocks are chiefly coarse, friable hornblende gneiss with abundant lenses of segregated hornblende and biotite. The strike varies from N. 15° W. to N. 30° W., and averages N. 25° W. From its trend, the Tallek was seen to be a strike-valley. The same may be said of the valley of the Kogârsuk, which mouths just west of Kipsimarvik. At the Post, thin sheets or dikes of eruptive rock cut the gneiss. They are light purplish-gray in color, and recall the anorthosites of the south. Gneiss similar to that at Kipsimarvik composes the northern and western slopes of the Kutyautak.

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[1] Rep. Geol. Surv. Canada, 1882–3–4, Pt. DD, pp. 15, 16.

At the head of the Tessyuyak, the variegated cliffs proved to be in largest part made up of badly weathered ferruginous and silicious schists, graphite gneiss, and graphite schist. With these was associated in considerable development a peculiar breccia of angular quartz fragments embedded in a black corneous matrix. The graphite occurs abundantly in the form of disseminated flakes. No large mass of the pure mineral was discovered in the short time at our disposal. That such a discovery is possible appears from the fact that a rounded piece of pure graphite measuring four by five inches has been found at the foot of the talus near the great alluvial fan; it is now in the possession of Mr. Ford.

The General Structure of the Coastal Belt.

From the foregoing account, it may be seen that, in the line of the long coastal section from Belle Isle Strait to Nachvak, Labrador is underlain by the crystalline complex. If, now, a review is made of the most important structural element, strike-direction, one cannot but conclude that the Archæan shield is rather definitely framed on this border, and that the average direction of the coast-line is related to the tectonic trend of the ancient mountain-system of which the Labrador plateau is a diminished remnant. (Plate 11, Table I.). A similar parallelism of structural trend and coast-line probably exists along the high mountain-belt of eastern Baffin Land as far as Lancaster Sound.[1] It should be stated that the brief table and the map do not represent the only evidence for this law as expressed in Labrador. Very often the general attitude of the crystalline schists could be determined from the schooner when under way, although no opportunity could then present itself for accurate measurement of the strike. The impression thus gained is sufficient to warrant our regarding the fidelity of the structure to a general N. W.–S. E. trend as of a higher order than is shown in the table or in the sketch-map. On the other hand, it is evident that no record

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[1] E. Suess, La Face de la Terre, 1900, vol. 2, p. 47.

TABLE I.

Strike-directions (true) in Newfoundland and Labrador.

Locality.	Character of Rocks.	Strike.	Remarks.
Great Bréhat, Newfoundland	slates, sandstones	N. 65° W.	stratification
Great Bréhat, Newfoundland	slates, sandstones	N. 35° E.	slaty cleavage
Fortune Bay, Newfoundland	slates	N. 25° E.	stratification
Kirpon Harbor, Newfoundland	slates and sandstones	N. 20°–30° E.	stratification
Assizes Harbor, Labrador	gneiss	N. 57°–82° E.	average N. 70° E.
St. Francis Harbor	gneiss	N. 45°–65° W.	average N. 60° W.
Pottle's Cove, West Bay	gneiss	N. 60° W.	linear parallel structure
Ice Tickle	gneiss	N. 85° W.	
Summer Cove, Aillik Bay	quartzitic sandstone	N. 20°–60° W.	stratification
Head of Aillik Bay	quartzite	N. 35° W.	stratification
Hopedale	gneiss	N. 55° W.	gneiss contorted
Quirk Tickle, 25 miles S. of Ford Harbor	gneiss	N. 45° W.	
Ford Harbor	gneiss	N. 5° E.	gneiss contorted
Island 2 miles N. of Ford Harbor	gneiss	N. 90° E.	
Island 6 miles N. of Ford Harbor	gneiss	N. 5° W.	
Cutthroat Tickle, 25 miles N. of Port Manvers	gneiss	N. 30° E.	gneiss contorted
Mugford Tickle	gneissic floor	ca. N. 45° W.	gneiss contorted
Mugford Tickle	sedimentary cover	ca. N. 45° W.	strike generalized
Hebron	gneiss, amphibolite	N. 45° W.	
Skynner's Cove, Nachvak Bay	gneisses	N. 5° W.	
Nine miles W. of Skynner's Cove, Nachvak Bay, north side	gneisses	N. 5° W.	
Great Cascade, Nachvak Bay	gneiss	N. 30°–35° W.	
Kipsimarvik	gneisses	N. 15°–30° W.	average N. 25° W.
Five miles from head of the Tessyuyak, Nachvak Bay, south side	gneiss	N. 35° W.	

of the tectonic axis of the system can be made in the broad areas of eruptive granites, diorites and gabbros so plentifully distributed along the coast. In the northern part, from Cape Chidley to Cape Mugford, the structural trend is represented in the present day topography of the Torngats and, to a less degree, of the Kaumajets. Elsewhere, there are only subordinate ranges of hills the directions of which lie parallel to the strike. The peculiar attitude of the east-west crest-line of the Kiglapait cannot be explained until the constitution of that range is known.

It would be of great interest to determine the relation between this Labrador trend and the structural axes of the Appalachian system. A hint of that relation was suggested by the structures observed at Great Bréhat Harbor in Newfoundland (twenty miles south of Cape Bauld). There a series of slates and feldspathic sandstones of unknown age but very similar to the Cambrian (?) sediments of Kirpon, shows stratification striking on the average N. 65° W. while a later and beautifully developed slaty cleavage strikes N. 35° E. The cleavage has an Appalachian trend; the folds show what may be regarded as the Labrador trend. If the future survey of northern Newfoundland proves that this association of structures is general, it may not be too bold to consider the region as at the nodal point of intersection of the two master structure lines of eastern North America.

These structural lines are likewise related respectively to the Labrador and Appalachian continental shelves which are so typically developed. Where the two shelves meet, we have the Grand Bank of Newfoundland. Although not accentuated among the theories of the Bank so far formulated, the possibility that the plateau on which it stands owes its origin to tectonic movements at the intersection of the Labrador and Appalachian structural axes, should not be overlooked. Thoulet seems to have thrown final discredit on the older view of Maury that the Bank has been built up from the deep sea by iceberg droppings; but Thoulet's replacing icebergs by coast-ice as the carrying agents still leaves the question open as to whether the materials dredged up from the Bank may not represent but a very shallow veneer coating the surface of a submerged mountain-plateau.

Observations on the Surface Geology.

The most important problems in connection with the surface geology of the coastal belt relate to glaciation and postglacial crustal movements. These processes became most interesting, perhaps, when viewed in the light of their effects on the existing topography. Among the incentives which the writer had to join the expedition was the need of more detailed observations than had yet been made on the general direction of ice-movement in glacial times; on the question of the non-glaciation of the high northern mountains; and on the "lunoid furrows" that were long ago found on the coast by Packard. The amount and character of postglacial uplift, the elevated beaches and other shore-forms associated with that emergence likewise invited as close study as time and circumstances would permit.

Glacial Markings; Direction of Ice-Movement.

Several visitors to the coast have repeatedly emphasized the difficulty of discovering there the glacial striæ and grooves which should normally appear on ledges so strongly ice-worn as those of Labrador. For this reason, it had been anticipated that our necessarily short halts at the different anchorages would not permit of our adding many localities to the few where the course of ice-movement has been determined. It was therefore an agreeable surprise to find ice-markings at nearly every landing place and often in great abundance. The intense power of the frost has, in postglacial time, certainly caused some obliteration of such records; but the non-discovery of these is much more likely to have been occasioned by the fact that search seems to have been hitherto largely confined to the shore-zone recently emerged from the sea. The evidence and amount of this emergence will be considered in the sequel. In the southern part of the coastal belt, it is only the higher points which, during the maximum postglacial depression of the land, remained above the sea. As the land arose, wave-action, coast-ice and the exceptional power of frost in the zone of flying spray, have tended to cause the destruction of all glacial marks within the belt of land thus exposed.

Selected readings of the directions followed by glacial striation are given in the following table (Table II.), and are plotted on the map. (Plate **13**.) It will be seen that at all elevations, both in the valleys and on the hill-tops, the ice-movement was outward from the central part of the peninsula. The result is to confirm the conclusion which has been based on five recorded single observations made at Hamilton Inlet, Indian Island, Davis Inlet, Nain, and Nachvak.[1]

Glacial Lunoid Furrows. — Chamberlin has shown, by the collection of many examples, that glacial markings *transverse* to the course of the

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[1] R. Bell, Scot. Geog. Mag. 1895, vol. 11, map accompanying text.

TABLE II.

Directions of Ice-Movement as shown by Grooves, Striæ, and Lunoid Furrows.

Locality.	Grooves and Striæ.		Lunoid Furrows.			
	Altitude in feet above High Water.	Direction (true).	Altitude in feet.	Character of bed-rock.	Occurrence: single (si), in series (se).	Direction (convexity downstream).
St. John's, Newfoundland	400	N. 90° E.				
Newell's Island, Greenspond, Newfoundland	6	S. 70° E.				
Fortune Bay, near Cape Bauld, Newfoundland	3	S. 20° E.				
St. Francis Harbor	5	S. 82° E.				
Head of West Bay	2	S. 85° E.				
New Harbor, near Tub Harbor	3	N. 85° W.				
Bake Apple Bight, Rodney Mundy Island	5	N. 55°–60° E.	5	fine-grained gneiss	si and se	N. 55°–60° E.
do.	20	N. 70° E.	20	do.	si	N. 70° E.
SW. side Rodney Mundy Id.	ca. 50	N. 55° E.	ca. 50	coarse gneiss and granitite	si	N. 55° E.
W. shore Sloop Harbor (Brig Harbor)	. . .	. . . . . .	250	coarse granitite	si and se	N. 65° E.
SW. flank of 335′ hill, Sloop Harbor	250	N. 80° E.	250	do.	si and se	N. 80° E.
Mainland NW. of Conical Id.	290	N. 25°–30° E.				
Ridge 3 miles W. of Pomiadluk Point	. . .	. . . . . .	250	granitite	si and se	N. 35° E.
do.	1170	N 30° E.	1170	do.	si	variable
Summer Cove, Aillik Bay	50	N. 35° E.	50	diorite	si and se	N. 35° E.
do.	200	N. 38°–40° E.	200	do.	si	N. 40° E.
E. side Aillik Bay	100	N. 40° E.				

TABLE II. *(continued)*.

LOCALITY.	GROOVES AND STRIÆ.		LUNOID FURROWS.			
	Altitude in feet above High Water.	Direction (true).	Altitude in feet.	Character of bed-rock.	Occurrence: single (si), in series (se).	Direction (convexity downstream).
Head of Aillik Bay	1000	N. 40° E.	1000	hornblende granite	si and se	N. 20°–40° E.
Hopedale	ca. 375	N. 29° E.	ca. 375	gneiss.	si	N. 40° E.
do.	ca. 375	N. 32° E.	do.	do.	si	N. 52° E.
do.	. . .	. . . . . .	do.	do.	se	N. 55° E.
do.	ca. 275	N. 43° E.	do.	do.	se	N. 43° E.
do.	. . .	. . . . . .	do.	do.	se	N. 30° E.
do.	. . .	. . . . . .	do.	do.	se	N. 35° E.
do.	. . .	. . . . . .	do.	trap dike	se	N. 37° E.
Quirk Tickle, 25 miles S. of Ford Harbor	300	N. 59°–62° E.	300	gneiss	si and se	N. 60° E.
Ford Harbor	295	N. 56° E.	295	gneiss	si	N. 50° E.
do.	380	N. 56° E.	390	gneiss	si	N. 43°–55° E.
Island 2½ miles N. of Ford Harbor	250	N. 65° E.	250	gneiss	si and se	N. 65° E.
do.	250	N. 53° E.	250	quartz vein	si and se	N. 65° E.
Port Manvers	2	N. 50° E.				
do.	300	N. 42° E.				
Cutthroat Tickle, 25 miles N. of Port Manvers	. .	. . . . . .	ca. 50	gneiss	si	N. 40° E.
Mugford Tickle	630	N. 85° E.[1]				
Hebron	ca. 100	N. 45° E.				
Kipsimarvik, Nachvak Bay .	200	S. 70° E.[1]	200	gneiss	si	N. 70° E.
Great Cascade, Nachvak Bay	700	S.[1]	700	gneiss	si	S.

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[1] Corresponding to the local character of the glaciation at these localities, the striæ and furrows have varying trends.

ice are of frequent occurrence.[1] In every case, the marking is typically curved and of lunate pattern, the convex side of the curve being directed upstream in the one class of markings, downstream in the other. There have yet lacked both criteria to distinguish the one division from the other and information as to the relative frequency of either kind in nature. Consequently, it has been hitherto impossible to use these cross-markings extensively as indications of the direction of ice-movement. With considerable interest and care the coastal belt was examined for light on the question.

Packard has described and figured the "glacial lunoid furrows" occurring at Indian Tickle just north of Hamilton Inlet. "These crescent-shaped depressions, which run transversely to the course of the bay, were from five to fourteen inches broad by three to nine inches long, and about an inch deep vertically in the rock. Their inner or concave edge pointed southwest, the bay running in a general S. W. and N. E. direction. They were scattered irregularly over a surface twenty feet square. When several followed in a line, two large ones were often succeeded by a couple one quarter as large or *vice versa*."[2] We owe the name "lunoid furrows" to De Laski, who gave the first clear account of them as they appear on the ledges about Penobscot Bay. The furrows are there from one inch to four or five feet in breadth. "They are lunate in figure, . . . their steep walls invariably looking towards the north, never directed *south* as stated in the "*Reports on the Scientific Survey*" [of Maine] for 1862, p. 383."[3] His furrows seem to be equivalent with the "crescentic gouges," "jumping gouges," and "disrupted gouges" of Chamberlin.

It was not far from Indian Tickle that the present writer also found the lunoid markings for the first time. At Bake Apple Bight on Rodney Mundy Island, excellent examples were discovered. The lunoid depressions, measuring from two to fifteen inches from horn to horn and from one quarter to one and a half inches deep in the middle of the curve, presented an appearance essentially similar to that described by Packard. The two slopes of the depression were always unequal. The longer one made an angle of from two to twenty degrees with the general surface of the *roche moutonnée ;* the other, limited above by the convex line bounding the marking in plan, made angles of from fifty to ninety degrees with the general ledge surface. The furrows or lunes occurred singly and also aligned in series. In both cases the axis of symmetry and the convex side of the curved pit were directed N. 55°–60° E. What made this locality of particular interest was the fact that one series of seven furrows lay on the stoss side of a ledge covered with undoubted glacial striæ and grooves. These were seen to lie in the axis of the lunes. The trend of the striæ was likewise N. 55°–60° E. Such a relation of parallelism between lune-axes and striæ was a strong witness to the glacial origin of the lunes, and it was found to exist in the case of the great majority of them at each locality on the coast. (See Table II.)

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[1] T. C. Chamberlin, U. S. Geol Sur., 7th Ann. Rept., 1885–86, p. 218–223.

[2] The Labrador Coast, p. 298.

[3] J. De Laski, Amer. Jour. Sci., 1864, ser. 2, vol. 37, p. 337.

The best exposures of the lunes discovered during the summer are at Pomiadluk Point, at Aillik Bay and at Hopedale. (Plate **7.**) At the head of Aillik Bay near the highest of the elevated shore-lines, a fine group of naked, highly polished *roches moutonnées* are marked with numerous lunes from two to three feet in span. On the east side of the bay at the shore near the prominent trap dikes opposite Summer Cove, the serial arrangement of the lunes is exceptionally well developed. In one instance twelve, and in another fifteen, of them were seen in line.

Single lunes, very rarely lunes grouped in series, are sometimes so situated that their axes of symmetry are widely divergent from the accompanying lines of striation. Such an attitude is, however, quite exceptional, and in general, the perfection of the lunate form is greatest when the axis of symmetry is orientated parallel to the striæ and grooves. Like the latter, the lunes were found most commonly on the stoss side of the glaciated ledge. As in Maine, the convex side of the lune is always directed downstream with reference to the moving ice-sheet that formed the grooves. This is true in the south and also at Nachvak where the glaciation was but local.

There seems to be no reasonable interpretation of the lunes that does not assign their location to glacial action. But it is difficult to imagine how either clean ice or boulders caught in the ice and dragged over a ledge could produce the actual furrow. From a somewhat prolonged study of the typical examples at Hopedale, the writer was led to believe that these lunes were only potential when the ice-sheet disappeared and to extend the same idea to all such furrows. The tension or shearing stress set up in the bed-rock by a boulder dragged along beneath the ice, must oftentimes be enormous. This must be so if boulders are really responsible for the deep striation and grooving of glaciated ledges. Such shearing stress may be easily conceived to be here and there partly relieved by the development of incipient cracks dipping gently forward and, at the same time, sloping inward from each side toward the line traced by the boulder. The formation of such a crack would, of course, be facilitated by a pre-existing tendency of the rock to exfoliate following surfaces parallel to the crack, but such a coincidence would be very rare. The integrity of the rock-surface will henceforth be endangered because frost can work upon these cracks in the same manner as it works on joint-planes. The actual hollows would thus owe their existence to the postglacial splitting action of frost, prying up and breaking off prismatic fragments of the rock until these fragments had reached a thickness appropriate to the steep inner face of the lune. The size of the lune is limited by the distance measured along the crack through which the rock has been rendered unsound.

The detailed features of the lunes seem to bear out this hypothesis. In every perfect or only partially completed furrow, a thin crack forms the prolongation of the gently sloping floor of the depression and is extended into the yet undisturbed rock at the horns where, in a little distance, the cracks disappear entirely. There is often a very decided difference in the freshness of the rock exposed on the steep and gentle slopes of the lune respectively. The latter may be distinctly weathered and lichen-covered, the former almost perfectly fresh and evidently so recently formed that no plant-life has had a chance to secure a foothold on the unaltered surface. This contrast between the two slopes is explicable by the hypothesis proposed; it forms a difficulty in the way of accepting any view which would derive a given lune in its present form from the direct action of the ice or its graving-tool.

While it may be anticipated that most lunes will be developed in parallel orientation with grooves, it will, by the shear-hypothesis, be no less certainly expected that tensions will be set up by many boulders not travelling in the direction of general ice-movement, and that lunes with quite different orientations will result. As we have seen already, the facts agree with this expectation. A further cause for the typical development of furrows may be looked for in the structure of the rock on which they occur. It may be for this reason that the lunes of Hopedale are so well fashioned. There the glacial grooves cut across the schistosity of the gneisses which will doubtless *tear* apart most easily in that transverse direction. Where the schistosity is not at right angles to the line joining lunes in sequence, the lunes are sometimes accordantly unsymmetrical, as if there were a tendency to exfoliation in a direction oblique to that line. Yet structure must play but a subordinate part in the manufacture of lunes, for they are found on such widely different rocks as the fine to medium-grained gneisses, coarse granitoid gneiss and coarse granite of Rodney Mundy Island, the granitites of Sloop Harbor and Pomiadluk Point, the diorite of Aillik Bay, the gneiss and trap of Hopedale and the vein quartz as exposed near Ford Harbor. Each rock has evidently acted as a more or less homogeneous body with reference to the deforming force.

Finally, it should be noted that postglacial frost is not of itself sufficient to produce the systematic form and arrangement of the lunoid markings. Examination of many ledges in Labrador on surfaces exposed by rifting since the ice epoch, failed to disclose anything similar to the phenomena described. To be sure, the familiar rough surfaces of ledges cleft by frost acting on structural and less regular cracks, is sufficiently analogous to the surface of a *roche moutonnée* covered with lunes, to suggest frost as the common cause for the damage done, but the irregular depressions of the first class lack the peculiar form and orientation of the second.

This explanation of the lunes naturally suggested experiment, but little has been done in that direction. When glass is scratched with a diamond point, a multitude of curved transverse cracks is generally produced. They are always short, highly inclined, and recall in a significant way the "serrated striæ" of Andrews,[1] the "cross-fractures" of N. H. Winchell,[2] the "crescentic cross-fractures" and "crescentic cracks" described by Chamberlin. They may be allied to "chatter-marks" as well. Russell has described others in the Sierra Nevada.[3] The convexities of these curved cracks are always symmetrical to the glacial striæ and are directed upstream, just as the convexities of the cracks in the glass of the experiment are symmetrical and directed in the sense opposite to the movement of the diamond. The "crescentic cracks" were seen in several localities in immediate association with lunes, but with an invariably reversed attitude of the convexities. The former class of markings, though commonly arranged in series, are much rarer than the lunes, and seldom appear on any but the finer-grained and more brittle rocks, quartzites, slates, and traps. They are usually under three inches in length and thus much smaller than the lunes. Being simply cracks, they do not form distinct hollows in the rock. Their steep inclination doubtless explains the fact that the frost has not produced such depressions as are likely to be developed where a crack has a low dip into the rock-surface.

While thus this experiment does not throw direct light on the interpretation of the lunoid furrows, it yet suggests an explanation for a related group of markings, and affords reason to believe that both groups are effects of the release of shearing stresses set up in the *roche moutonnée* by a striating boulder.

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[1] E. Andrews, Amer. Jour. Sci. 1883, ser. 3, vol. 26, p. 101.

[2] Geol. Nat. Hist. Sur. Minn., 1884, vol. 1, p. 548.

[3] I. C. Russell, U. S. Geol., Sur. 8th Ann. Rept., 1889, p. 367.

Packard's early theory of the furrows has been amended to a form which may be stated in his own words:

> "The curved and crescentic or gouge shape of the mark appears to be due to the fact (1) that the glacier carried or pushed a more or less angular boulder over a granite nubble or spur, so that the pressure was greater than at other points in the valley [the Aar Valley]; (2) the more or less rounded boulder, with its lower or under side perhaps somewhat flat, and so situated that the ice rested only on the top, occasioned greater local pressure than where no boulders were present; (3) the boulder meeting with a slight obstacle suddenly stopped, and the ice pushing it from behind caused it to slightly tip, so that an immense pressure was brought to bear on the small surface, causing the formation of a gouge-like crescentic hollow, with the concavity towards the origin of the motion, *i.e.*, facing up the valley.
>
> "In making my first explanation I wrongly inferred that there might be an 'advancing and receding motion of the glacier,' so as to cause the stone to turn over.
>
> "In some way, then, due both to the striking or pushing force of the glacier, and to the local pressure resulting from the presence of a boulder between the ice and the rock-surface, the boulder was not as with the rest of the ground-moraine, pushed gradually and slowly onward, but hitched, thus causing it to break off the lunoid fragment on a surface peculiarly liable, under great local pressure, to exfoliate."[1]

If the writer correctly understand Packard's view, both his hypothesis and the shear hypothesis agree in removing the furrows from the category of "chatter-marks," which imply that the gouging-tool must have been lifted clear of the rock-surface in order to deliver its smiting blow. That true lunoid furrows may be formed at intervals along an otherwise continuous groove is shown in Figs. 32, 33, and 34 of Chamberlin's classic paper.[2] It is clear, in each case, that the boulder must have pressed the ledge with great force as it traversed the inter-furrow space. Packard makes the hollow as well as the tendency to exfoliate date from the time of the actual passage of the boulder over the rock; but he does not show how localized downward pressure could produce a crescentiform hollow with a steep scarp facing upstream.

The main conclusions from these considerations are: First, that crescentic cracks and lunoid furrows may be distinguished in the field; secondly, that while often very abundant, they form valuable criteria for the direction of ice-motion in a region once glaciated, and still strongly frost-bitten in the winter-season at least; and, lastly, that both kinds of marking may be regarded as directly or indirectly the product of shearing stress set up in bed-rock at the gouging corner of a boulder held in the advancing ice.

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[1] Amer. Geol., Feb. 1890, p. 105.

[2] U. S. Geol. Surv., 7th Ann. Rept., 1885–86, p. 219–220.

THE GLACIAL DEPOSITS.

Nothing is more striking in the glacial geology of the southern part of the coastal belt than the almost complete absence of drift deposits. Above the highest shore-line registering the limit of postglacial submergence, isolated boulders resting on bare rock, or small patches of till a few inches or feet in thickness, represent the only glacial accumulations seen at any of our landing-places save one of all those south of Nachvak Bay. North of Cape Porcupine and elsewhere, it is true, washed drift that has been assorted and collected in the form of bay-plains and beaches now elevated, were found; but extensive deposits either directly ice-laid or distributed by glacial streams, normally failed. The exception referred to, applies to a small but well-defined frontal moraine situated on the mainland opposite Copper Island near Seal Island Harbor. Approaching the mainland through a narrow tickle, we were struck by the sight of a flat-topped terrace, steeply scarped at the shore. This cliff, averaging some fifty feet in height, was found to be composed of typical till strongly charged with boulders of gnarled schists and gneisses, a peculiar hornblende syenite, micaceous trap, pegmatite, aplite and vein quartz. The beach facing the moraine had greater variety of composition than any other noted during the summer. Most of the boulders were clearly erratic. The moraine is bilobate in plan, the curved ridge trending roughly north and south. It is a curving wall one hundred feet in maximum height and about a mile and a half in length. The concave side of the curve looks toward the mouth of a strong east–west valley opening toward the sea through a range of hills. The latter approach one thousand feet in altitude and seem to have harbored at least this one valley glacier in the closing stage of the ice period. On account of the rarity of such deposits, and on account of its fine development, it would have been of interest to study it in greater detail, but no opportunity to do so was afforded.

THE GLACIATION OF THE TORNGATS.

In 1860, Lieber noted that on the mainland opposite Aulatsivik Island, "wild volcanic-looking mountains form a water-shed in the interior, whose craggy peaks have evidently never been ground down by land-ice into domes and rounded tops." Bell, in 1884, published his observations on the Torngats. He stated: "The mountains around Nachvak are steep, rough-sided, peaked, and serrated, and have no appearance of having been glaciated, excepting close to the sea-level. The rocks are softened, eroded, and deeply decayed. . . . Throughout the drift period, the top of the coast range of the Labrador stood above the ice and was not glaciated, especially the high northern part." [1]

But this serrate topography is not of itself sufficient to disprove that the glaciation was general in the Torngats; it implies with certainty only that the glaciation of the range was *weak* at higher levels at the time when the hummocky plateau of southern Labrador was remodelled by the ice. Tarr has shown that, notwithstanding the angularity of its summits, Mt. Ktaadn in Maine was completely covered by ice in the last glacial epoch. The present form is understood in the light of the facts that Tarr has emphasized: (1) The rapidity of frost attack is so great at high altitudes that the shape of a glaciated knob may be significantly changed even in postglacial time. (2) The summits have been longer exposed to the weather than the valleys, since the latter would be occupied by local glaciers during late glacial time. (3) Although the summit was ice-covered, it would presumably be above the zone of maximum glaciation. (4) The lack of timber in the higher parts of the mountain would give the weather permission to produce serrate topography which would not be expected in the lower vegetated belt.[2] In summarizing the results of his studies of the Cornell glacier, Tarr notes further strictures on the same criterion of non-glaciation.[3] He states in effect that we should expect less erosion by ice in the higher parts, because of the slower motion of the ice in the upstream portion, and because of the clean character of the ice above the débris zone. The valleys should necessarily show more intense erosion than the mountain-tops, since thick glacier ice would appear first in the valleys as the ice-cap waxes, and still exists there after the waning ice-cap had deserted the summits. He has, moreover, found erratics on Mt. Schurmann, a ragged nunatak in the Cornell glacier. Lastly, he notes that serrateness may be only apparent, the impression of raggedness being due to the common position of the observer on the lee or down-stream side of a glaciated headland, as he approaches such a coast as that of West Greenland. While it is true that the serrateness of the Torngats is real and extensively developed, it will be well to present the evidence now in hand, which shows that, above a certain relatively low line, the range was, during the last advance of the great ice-sheet, not covered by a glacial mantle differing in any important way from the snow-blanket which overlies the country during the present winters.

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[1] Rep. Geol. Sur. Canada, 1884, Part DD, pp. 14 and 37; cf. Report for 1885, Part DD, p. 7, and Scottish Geog. Mag., Vol. 11, 1895, p. 340.

[2] R. S. Tarr, Bull. Geol. Soc. Amer., 1900, Vol. 11, p. 437.

[3] Bull. Geol. Soc. Amer., 1897, Vol. 8, p. 252.

It is important to note that the discussion of the question will refer simply to the last advance of the ice. Until it has been determined whether there was once an interglacial period in Labrador corresponding to that recorded in the United States and southern Canada, we cannot be sure that a glacial topography, developed during the first advance, was not destroyed during interglacial time and during the time occupied in the second advance. It seems probable that the interglacial interval was longer near the zone of great terminal moraines than in Canada. Still further north the ice may have lain on the country throughout the whole glacial epoch. On the other hand, the Torngats may hold exactly the same relation to the rest of the peninsula as that of the Lofoden Islands to the Scandinavian mainland. An Alpine relief characterizes the island group to-day, although the ice-cap of the first glacial advance ran over the group far out into the Atlantic.

The first attempt to solve the problem was made on the slopes of Mt. Ford. Ascending the mountain on the west side, typical *roches moutonnées* and undoubted erratics cease at the sixteen hundred-foot contour. Above this, to the summit, the slope is one continuous Felsenmeer. Although unremitting search was carried on during the ascent, not a single erratic piece of rock was discovered above the contour mentioned. The creeping, frost-driven and snow-driven, fragments of ferruginous gneisses, trap, vein quartz, and syenite were found to be universally sharp-cornered, never subangular, and always deeply weathered. The few ledges protruding through the Felsenmeer were likewise profoundly affected by frost and general weathering, and nowhere presented the familiar smooth surface of a glaciated nubble of rock. While these contrasts between the Felsenmeer fragments and decayed ledges above and the fresh subangular erratics and *roches moutonnées* less than five hundred feet below, were very marked, there yet remained the possibility that the Felsenmeer really covered well glaciated bed-rock over which the rock fragments have streamed in postglacial times. The rarity of the ledges between sixteen hundred feet and the summit was such as not to permit of a satisfactory conclusion based on the study of this one mountain-slope. On the south side, where the descent of Mt. Ford was made toward the cascade, more significant testimony was furnished by the ledges. Two of these, each from one to two acres in extent, occur on the *flat* top of spurs measured at thirty-two hundred and twenty-five hundred feet respectively. In both cases the outcropping rock is a decomposed, light-colored gneiss cut by numerous wide bands of black trap. Each spur-top is separated from the main mountain by a col; rock-slides or snow-slides would not sweep over the spurs from the higher slopes, and thus disturb from their original positions any erratics that may have been dropped on the spurs by a glacier. Nor would general creep have removed such erratics. Wherever ledges at all heights up to twelve hundred feet and above the highest shore-line of postglacial submergence, were examined elsewhere in Labrador, glacial boulders were very plentiful. Thus, under essentially similar climatic conditions, the hills about Hebron have preserved their coating of glacial drift even on slopes much steeper than on these spurs of Mt. Ford. It was, therefore, a matter of no small moment to find, after prolonged search, an utter failure of erratic material on both spurs. Here, too, the bed-rock shows no trace of glacial smoothing.

At sixteen hundred feet, in the notch between Mount Elizabeth and Mount Ford, the Felsenmeer ceases in a steep talus-like slope. Below that level the valley-floor is composed of typical, well-polished and striated *roches moutonnées* covered with fresh subangular boulders, which, from their position, being often delicately poised on the tops of nubbles sloping outward on all sides, were evidently not brought thither from up the valley by waste-streams or snow-creep of present day dimensions. The erratic nature of these boulders of diorite and fine grained ferruginous schist resting on coarse hornblende gneiss, was clear in the field. The ledges, though often as steep as others occurring above the sixteen hundred-foot level, and though similarly devoid of vegetation, are yet hardly at all riven by the frost. The striæ and grooves are well developed and are invariably directed down the valley. At the cascade, "Korlortoâluk," they are confluent with grooves transverse to themselves and running seaward parallel to Nachvak Bay. Both sets of grooves agree with corresponding sets of lunoid furrows in indicating that the Nachvak trunk glacier flowed eastward and received at the cascade a south-flowing tributary. (Plate **12**.)

Thus, below sixteen hundred feet on the west and south slopes of Mt. Ford, there is a well glaciated zone. Above that level, steep slopes of streaming Felsenmeer have deeply covered the ledges. At twenty-one hundred feet and above, the ledges are in the utmost contrast with those lower down. This contrast is such as to enforce the belief that glacier ice did not reach higher than about twenty-one hundred feet above the present sealevel.

Similar evidence was found on Mt. Elizabeth, and the limit of glaciation was put at the same level as on Mt. Ford.

Although of no special importance in connection with the problem now under discussion, brief reference may be made to a curious novelty that was found in the search for the glacial limit on the twenty-five hundred-foot ridge east of the cascade, Korlortoâluk. About three-eighths of a mile from the waterfall at the measured altitude of sixteen hundred and twenty feet, there occurs a shallow col drained southward into the Bay and northward into the main hanging valley. This col is floored over completely with glacial boulders packed closely together so as to form two smoothly graded slopes gently declining in the directions of the drainage-lines mentioned. The total length of the doubly graded pavement is about two hundred and fifty yards. At either end it terminates in much steeper slopes of bed-rock. The width varies from thirty to fifty yards. The pavement is bounded laterally by glaciated ledges covered with erratics ; the latter are plainly in a much fresher condition than the materials of the general Felsenmeer. That the deposit is not of the nature of a barrier-beach is clear from the subangular form of the boulders that show no sign of having been water-worn. There is, moreover, unequivocal proof that the land during postglacial time was not submerged more than about two hundred and fifty feet at Nachvak Bay. Similar doubly graded slopes of rock-fragments were discovered on Mt. Elizabeth at altitudes of twenty-two hundred and twenty-three hundred and fifty feet, but these seemed to be simply parts of the ordinary streaming Felsenmeer, as the rock-fragments were quite angular and deeply weathered. The two types may be analogous in origin, but it is difficult to imagine how an ice-sheet could veneer a col deeply and completely with typically ice-worn boulders. Without even a working hypothesis to go upon, the question of origin must here be left unanswered.

But the most satisfactory locality yet studied occurs in the Kogârsuk Valley. About two and a half miles from the delta of the brook and on the eastern slope of Kaputyat Mountain there is a series of ten lateral moraines at elevations of from seven hundred and fifty to seventeen hundred feet above sealevel (Fig. 3). The deposits are composed of large, relatively fresh, subangular boulders with a small intermixture of clay. The form of each moraine is that of a steeply scarped bench or of a distinct wall. One of the best defined ridges, at an elevation of twelve hundred feet, is from twenty to fifty feet high and some four hundred yards in length. The longitudinal and transverse profiles are in every way similar to those of a Swiss lateral moraine. Though generally arranged parallel to the valley-wall, in some instances the moraine is winged out from it and is then characterized by many shallow kettles and small ponds. The general slope of the moraine-crests is to the southward toward Nachvak Bay, and is sympathetic with the inclination of three well-marked rock-benches on the east side of the Kogârsuk Valley. Combining the evidence of groovings with these facts, it was evident that the glacier that was responsible for the moraines and benches flowed southward toward

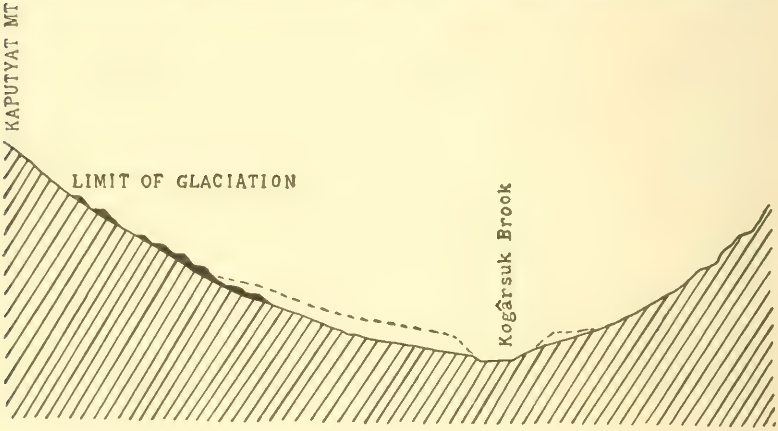

FIGURE 3. — Cross-section of the Kogârsuk Valley showing its bed-rock floor overlain by lateral moraines (solid black) and trenched ground moraine (dotted lines). Rock-benches on the right. Looking north.

the great fiord. At twelve hundred and fifty feet on the flat top of the long spur which lies in the angle between the fiord and the brook, a crescent-shaped frontal moraine nearly four hundred yards in length lies, as it were, stranded there, as the Kogârsuk glacier retreated to its narrower channel on the east.

The belt of lateral moraines, here and there broken down in the paths of entering side streams, extends five miles to the northward from its southern extremity. A little more than three miles from the mouth of the brook, the valley widens out in a notably flat stretch estimated to be at least eight miles in length and from one to three miles in width. The bed-rock is here deeply buried in a till-deposit which seems to be transitional into the terraced lateral moraines on the west much after the manner of similar deposits in the High Sierras.[1] It abuts directly against the bed-rock on the east where the lateral moraines are wanting. This great deposit, so unlike in composition and form any other considerable glacial product seen in northern Labrador, was interpreted in the field as a ground moraine. It is trenched to a depth of more than five hundred feet by the Kogârsuk, toward which the rough plain slopes on either side.

From seventeen hundred to nineteen hundred feet on Kaputyat mountain, fresh subangular erratics rest on the ledges. This zone is as recognizably glaciated as that of the morainal ridges below. But from nineteen hundred to two thousand and fifty feet there occurred an abrupt transition into the region of an interrupted, typical Felsenmeer in no way markedly different from that on Mt. Ford. The rock-fragments are sharp-angled, rusted to the deep brown color of the adjacent ledges and strikingly different from the gray tints of the fresher ledges and erratics below. The transition zone is represented, too, not only in the color, but also in the form, of the ledges. Though rapid, the change can be distinctly observed from well smoothed profiles to those which are extremely ragged. These various phases of transition would be expected if the glaciation of the valley had been purely local; its existence in no way obscures the essential contrast of the two limiting zones.

No erratics could be found above two thousand and fifty feet. Above and below the transition zone, the general declivity is constant in amount, and we cannot ascribe their absence above the zone to a more rapid rate of creeping. The residence of erratics on the tops of isolated spurs in the lowest zone forbids the idea that they could have crept thither from the higher zones.

The limit of glaciation in the Kogârsuk Valley is seen to be very nearly of the same altitude as on the flanks of Mt. Ford and Mt. Elizabeth, namely at twenty-one hundred feet above the sea.

Taking the Nachvak region as a sample of the whole of the higher Torngats, the general conclusion is that these mountains have not suffered, during the last advance of the ice-cap, even the limited amount of glacial erosion that may be discerned on the summits of Mt. Ktaadn, the Presidential range of New Hampshire, Ben Nevis and the neighboring peaked mountains of the western Scottish highlands, or the ragged outliers of the Scandinavian plateau. It is probable that the higher parts of the Kiglapait and the Kaumajet massifs similarly formed nunataks overlooking the late Pleistocene ice-sheet.

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[1] I. C. Russell, U. S. Geol. Sur., 8th Ann. Rep., 1889, p. 360.

The Zone of Postglacial Emergence in Northeastern Labrador and in Newfoundland.

The path of the "Brave" was such as always to keep us in view of memorials of recent uplift of the land. These were found to be so numerous and so striking that one's note-books rapidly filled with the data of their nature and occurrence. If all other sources of geological interest failed on the coast, the singularly fresh records of emergence are yet sufficient to refute Lieber's statement that "the geology of Labrador is of extraordinarily little interest." The account of the cruise would be incomplete without reference being made to the observations made in connection with this subject.

Packard's summary in "The Labrador Coast" makes it unnecessary to review the earlier studies. Still more recently, Low has published the elevations of raised beaches in Ungava Bay, Hudson's Bay, James Bay, and in the interior of the peninsula.[1] So far as known, all the beaches described by both authors are of postglacial date and are related to the elevated shore-lines early described in the Gulf of St. Lawrence. On account, however, of the scant information we possess concerning the actual heights of the Atlantic coast beaches, no very definite correlation of these with one another or with the beaches farther west has yet been made. Thus an accurate idea of the amount or kind of elevatory movement that the Labrador peninsula has suffered in postglacial time, is yet lacking. What light last summer's coastal studies throw on the question will first engage our attention.

The barometric method was used in fixing elevations. Four standard compensated aneroids were employed. The accessibility of the sea-level and of the British Admiralty's triangulation stations as check-points, of course, give the aneroid an exceptionally large share of advantage as compared with that enjoyed by the same instrument working inland. It is believed that the error seldom exceeded five feet. At any rate, the accuracy obtained was sufficient for the main purposes of the study.

It was found to be impossible to group the beaches with reference to distinct levels, the deformation of which would indicate the type or types of crustal movement in postglacial time. At only one anchorage was there discovered a correspondence among the different beaches which showed that there were special beach-building periods in the whole time since uplift began. This was at Kirpon Harbor near Cape

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[1] A. P. Low, Rep. Geol. Surv. Can. 1895, p. 308, and 1899, Part L.

Bauld, Newfoundland. Wave-built terraces were found at six, twenty-two, thirty-five, and seventy feet above high-water on the hills overlooking the harbor itself. Others measured six, twenty-two, thirty-five and one hundred and twenty feet in Mauve (Noddy) Bay. A third set on Kirpon Island measured six, twenty-two, thirty-five, seventy, and one hundred and twenty feet, and were particularly well exposed in Grand Galets Bay. The one hundred and twenty-foot beach-terraces match well with the very strong rock-benches on the headlands composed of the relatively soft slates about the entrance to Mauve Bay. At Grand Galets, where the indentation is deep both vertically and horizontally, terraces at all the levels may be seen. We hoped to find similar correspondences among the beaches across the Straits, but failed to do so. In Labrador nothing comparable to the beautiful system underlying the occurrence of the warped ancient shore-lines of the Great Lakes could be determined. It is impossible to deny that the uplift has been on the Labrador coast, as so often illustrated elsewhere, spasmodic, but it does not follow that this intermittent character will be reflected in the raised beaches of the present day. In most cases an ancient beach has been composed and located where it is because of special local conditions of formation and not because there occurred a halt in the uplifting process. Deposition takes place wherever the required protection against under-tow and shore-ice in the presence of appropriate off-shore depth, is afforded. (Plate **10**.) If the hardness of the rocks, the off-shore depth, or the fetch and direction of the more effective waves were to change at a given point, the balance of conditions leading to beach-formation would be destroyed. Thus a beach growing under the former circumstances, might grow faster under the new; or, on the other hand, be demolished, its débris forming a new beach elsewhere or helping to raise the sea-floor whither it was dragged. Probably no single factor in producing such changes on the Labrador coast has been so important as vertical movements of the land.

Not only, thus, will those beaches that were really formed during halts in the elevatory process, be difficult to distinguish from those developed in protected bays as uplift takes place; the record of halts will be further masked by the appearance of beach-like deposits laid down on steep-to shores in several fathoms of water. An interesting example has been described by Packard as "a truly noble beach." It occurs on the south side of Sloop Harbor. It is about two hundred yards long and roughly graded from the one hundred and fifty-five-foot crest of the ridge enclosing the harbor on this side to the shore two hundred and fifty yards away. Most impressive was the view along the rugged accumulations of boulders, rounded or subangular and varying in diameter from six to ten feet. From the position of the "beach," it was clear that the enormous energy required to round off such boulders was derived from waves of great fetch and moving in water of some depth from the southward; that is, it looks as if the cyclopean Felsenmeer had been built up in the lee of the ridge at a time when the ridge was here entirely submerged. The heavy Atlantic breakers of that time rifted the masses from the bed-rock and threw them over the col into the protected place where we now see them.

When we also consider the fact that long stretches of the coast are too exposed to permit of the growth of beaches at all, it is clear that the discovery of general levels may be made only after several seasons of careful field-work. Even after such effort be expended, the quest may prove to be fruitless. The work that was done in this one summer certainly led to negative results.

LOCATION OF THE HIGHEST ELEVATED SHORE-LINE. — On the other hand, a considerable degree of success was attained in the attempt to fix the *highest* shore-line, *i. e.*, the most ancient of postglacial levels now warped into a form which is a resultant of all positive and negative movements of the land since uplift began. Along the eleven hundred miles of coast from St. John's to Cape Chidley, no trustworthy estimate had been made as to the position of this old level. The desirability of filling in this gap in our knowledge is evident. De Geer has attempted to construct a map of northeastern North America similar to his classic one of the Scandinavian Peninsula, showing the character of postglacial uplift.[1] His "isobases" join all points of equal uplift. The map was left incomplete, since, for lack of information, the isobasic curves could not be produced into eastern Labrador. Yet for the purposes of geological theory, it is of the highest importance that this edge of the glaciated tract should be similarly treated.

The principle used in the determination of the highest shore-line seems to have been in the minds of Packard and Hind during their early visits to the coast, but was applied by them only very locally. Shaler, and later Stone, used it on the coast of Maine, and it has been employed in Baffin's Land by Watson and Tarr, and still more extensively in Norway, Sweden, and Finland by De Geer and other Scandinavian geologists. The criterion is, in a word, that, on appropriate headlands and hills where the surf from the open ocean can be felt on a glaciated shore during submergence, the present lower limit of undisturbed glacial erratics marks with but subordinate error the highest shore-line of postglacial submergence.

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[1] G. De Geer, Proc. Bost. Soc. Nat. Hist., 1892, vol. 25, p. 454.

For the first time during the cruise, conclusive evidence of the value of the criterion on the Labrador shore was obtained at Ice Tickle Harbor. It is of importance to review the conditions under which it was there employed. These conditions are essentially the same as those found at the numerous other stations occupied up and down the coast.

The situation, topography, and bed-rock geology of the islands on either side of the tickle have already been described (p. 213). The dark-hued trap-ridges are dotted over with light gray gneissic boulders offering strong contrast in color and composition with the ledges beneath. These boulders are subangular, not water-worn, often greatly decomposed, and have evidently lain long in their present positions. They are associated with a small proportion of boulder-clay which is, in places, actively creeping down the slopes. Occasionally the boulders are perched and may be easily rocked with the hand. All these boulder-covered ridges are over 265 feet high. Those of less height are devoid of boulders; those of greater height may be divided into a boulder-covered and a boulderless zone separated from each other by the 265-foot contour. (Plate 8.)

That the boulders are truly glacial erratics, reposing practically where the great Labrador ice-sheet left them, can hardly be doubted. The only alternative origins which have suggested themselves are two in number. Either the boulders, originally deposited elsewhere by the land-ice, were thrown up by strong storm-waves, or they were brought thither by floe- or shore-ice. In spite of the unlikelihood of these hypotheses, it was held that evidence should be obtained that would thoroughly test them. The long ridge on the southern shore of Ice Tickle Island threw ample light on the question, and serves as an extremely good type locality for demonstrating the criterion.

This ridge, over a mile in length, and generally about three hundred feet in height (325 feet, measured barometrically at the highest point) is a residual hill situated where a thick trap dike projects above the softer gneisses. Its axial trend is roughly east and west. Its sides are very steep, running together at a sharp edge, whence one looks directly out over Hamilton Inlet on the south and over a deep valley and beyond over the open sea north of the island. There seemed to be no possibility that waves breaking on the ridge, submerged to the 300-foot, or any higher contour, could under normal conditions, transport large boulders from the adjacent depths and lodge them, delicately poised, on the summit of the ridge. The explanation by floating ice would leave out of account the great rarity of trap boulders, though these should be the commonest, since, during submergence, the only shoals for many miles around whence floating ice might derive rock-fragments other than glacial erratics, would be underlain by the trap of the present hills. Still less would the sudden cessation of this sort of deposition at the 265-foot level as the land arose, be explained. Finally, both hypotheses suffer from the difficulty that boulders, perched on the ridge-summit as we now see them, could not be left *in situ* if the rate of uplift were anything else than catastrophic. A single heavy storm from the southward would doubtless suffice to sweep all loose material from their precarious position. The conclusion that the boulder-covered zone has never been submerged since the general ice-sheet retreated from the country, cannot be escaped. On the other hand, the boulderless zone is a wave-swept zone.

Other evidences for former submergence of the lower zone are clear and convincing. The smooth, unbroken surfaces of the *roches moutonnées* above 265 feet contrast strongly with the jagged and riven ledges below that level. At the upper limit of the boulderless zone, low, but steep and rugged cliffs look northward over frequent pockets and graded slopes of well-rounded pebbles. Similar deposits were observed at 145, 155, and 175 feet, while an unusually fine boulder-beach fifty yards long and twenty in width occurs at 205 feet. The boulders, averaging six inches in diameter, are not covered with vegetation, and bear remarkable resemblance to the raised beaches of Hogland in the Gulf of Finland. Such beaches are rare on both Ice Tickle Island and on Rodney Mundy Island. That they were here not discovered more plentifully is due to the general steepness of the ridges and the consequent lack of places of lodgment for loose material; to the hardness of the rocks hereabouts, coupled with the shortness of the time allowed for beach-building; and to the abundance of moss and other peat-formers that develop thick vegetable mantles over most graded slopes. An indication of the great variety of form assumed by elevated sea-chasms, benches, and boulder-deposits in the wave-swept zone at other localities, will appear in the following pages.

Occasionally it was found that single boulders in exposed situations occurred below the accepted level of the highest shore-line. These were either too large to be moved by the waves, or had rolled down from the upper zone since emergence had taken place. Greater care had to be exercised with slopes covered with streaming drift. In such cases, masses of clay, small rock-fragments, and boulders compose small tongues or scalloped terraces, the forms assumed by these materials as they are washed each year farther and farther down the hill-side. Similar terraces were photographed in Alaska by members of the Harriman Expedition.

Between landing-places, a tolerably good idea of the altitude of the highest shore-line could sometimes be attained. The treeless nature of the headlands caused the boulders of the upper zone to stand out with great clearness in the different profiles of the hills. As our schooner hugged the shore pretty closely on the northward, or "downward" journey, the line could often be located within an error of ten or twenty feet. If by good fortune, the cairn of a triangulation station were also in the view, it was often possible to secure quite useful information concerning the line. A difficulty in using the cairns was, however, found along the northern half of the coast. Not only are the charts of that section very incomplete and inaccurate; it was often not possible to distinguish the Admiralty cairns from those erected in great numbers by the Eskimo on prominent hills, — the "American men" of the fishermen.

Finally, it is worth noting that the boulder-limit does not exactly represent the actual former level of the sea, which will be a few feet below the limit. The ancient waves would have an effective reach for some distance above high-water mark.

Table III. summarizes the results of the observations on the highest shore-line. At most of the landing-places the land was high enough to show the line. At others, all the hills ascended were found to be clean swept. (Plate 8.) For each of the latter the elevation of the highest hill is given in the table. There also appear the estimated heights of the line determined from the schooner on islands and headlands surmounted by triangulation cairns. The table shows that the uplift on the Labrador coast has been greatest near Hopedale. Hamilton Inlet owes in part its depth, and, indeed, its very existence as an inlet (it is but 10 fathoms deep at the Narrows), to the fact that the part of the plateau on which it lies has not been elevated as much as the land to north and to south. The line rapidly rises as it crosses the Strait of Belle Isle, and seems to be about 500 feet in height along the whole eastern shore of Newfoundland. It was last observed at St. John's. Signal Hill (508 feet) is clean swept. The ridge on the south side of the Narrows is boulder-covered and the line was estimated at the dis-

TABLE III.

OBSERVED HEIGHTS OF THE HIGHEST POSTGLACIAL SHORE-LINE IN NEWFOUNDLAND AND LABRADOR.

NOTE. — Numbers enclosed in brackets refer to altitudes estimated at a distance by the use of the boulder limit and the triangulated points of the Admiralty charts. Numbers followed by the plus sign give the heights of clean-swept hills too low to show the highest shore-line.

LOCALITY.	AVERAGE ALTITUDE OBTAINED FOR HIGHEST SHORE-LINE, IN FEET.	ALTITUDES OF BEACHES IN THE WAVE-SWEPT ZONE.
St. John's, Newfoundland .	508 + [575]	washed gravels at ca. 400 feet on Signal Hill
Cape Rouge Harbor, Newfoundland	505	
Kirpon Itland, Newfoundland	450 +	beaches at 6, 22, 35, 70, 120 feet
St. Francis Harbor . . .	365	rolled boulders at 260 feet
Venison Tickle	[325–340]	
Near Domino Harbor . .	[ca. 300]	
Gready	[260]	
Ice Tickle	265	washed gravels at 145, 155, 175, 250, 255 feet; beaches at 140, 205 feet
Sloop Harbor	265	beaches at 115, 140, 160, 215 feet
Mainland N. W. of Conical Island	290 +	
Pomiadluk Point	345	gravels and beaches at 55, 65, 245, 250, 255, 260, 275, 315, 320, 335 feet
Cape Strawberry . . .	[350]	
Aillik Bay	355	beaches (many below 100 feet); rolled boulders at 255 feet
Hopedale	390	beaches at 125, 270, 370, 385 feet
Quirk Tickle, 25 miles S. of Ford Harbor . . .	340	rolled boulders at 250 feet; beaches at various levels
Ford Harbor	290	beaches at 145, 200, 245 feet; many at lower levels
Black Island Harbor (Newark Island) . . .	290	several barrier-beaches at 50 feet
Port Manvers	285	beaches and bars at 210 feet and lower
Cutthroat Tickle, 25 miles N. of Port Manvers . .	270	
Mugford Tickle	265	
Hebron	260	several beaches up to 225 feet
Kipsimarvik, Nachvak Bay	250	many small pockets of beach-gravels up to 185 feet

tance of the width of the Narrows, to lie at the 575-foot contour. No opportunity presented itself for the ascent of this southern ridge; hence the line at St. John's could not be placed more accurately.

The observations at the Hudson's Bay Post in Nachvak Bay gave as indisputable evidence of the relatively low position of the highest shore-line as was obtained at the other coast stations. The position of the boulder-limit and the entire absence of elevated beaches at heights greater than 250 feet mean that that elevation is very close to the level of greatest postglacial submergence.

If the record of the table be put in graphic form (Figure 4) it becomes still more evident that along the eleven hundred miles of coast the elevation has been differential. The pronounced warping of the highest shore line is incompatible with the view that changes in the position of the level of the sea over great stretches of the earth's surface, are produced solely by independent vertical movements of the surface of the ocean.

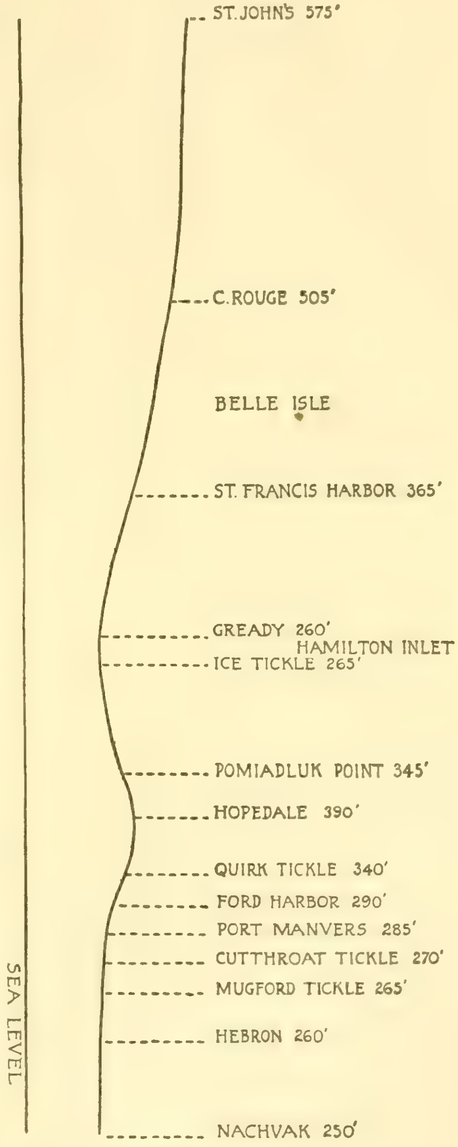

FIGURE 4. — Curve showing the present warped condition of the highest postglacial shore-line between St. John's and Nachvak Bay.

Along the line on which our observations were made, there has been unequal positive uplift of the earth's crust. The force responsible for this great piece of work has been applied locally and in varying degree. The result is that to-day the actual distance from the centre of the earth of every point on that line is greater than it was at the close of the glacial period.

The coastal belt shows a degree of elevation considerably less than that demonstrated for the region east and southeast of James Bay. Supplementing the data of Low's and De Geer's maps with the writer's observations on the northeastern coast, one is led to the conclusion that the uplift of the glaciated tract of this part of America has been greatest near the region of the central névé.[1] The result is to strengthen De Geer's parallel between the postglacial behavior of the earth's crust in northeastern North America and in northwestern Europe. The bearing of this conclusion on the theory of isostasy is obvious. Perhaps the relatively great uplift of Newfoundland is connected with the local character of its glaciation, which, according to Chamberlain, was not due to an extension of the ice-fields of the mainland.[2]

Boulder Barricades. — There is not wanting an indication that on the Labrador coast, at least, the land is higher to-day than in any other part of postglacial time. Wherever the shore slopes are not too steep, the coast is belted with lines of innumerable large boulders visible between low and half tides. These accumulations may be called "barricades." The name is recognized as appropriate by any one who attempts to land at low water by forcing a small boat through a gap in the nearly submerged wall of boulders. The barricade is situated twenty to one hundred or more feet from the shore according to the slope of the foreshore; the distance is greater as the slope is the more gentle. Plate **9** gives a typical view of one seen at Ford Harbor. Lyell long since figured an example in the "Principles of Geology (ed. 11, 1892, Vol. I. p. 381).

Of particular significance is the fact that, in practically every case where one of these accumulations was examined, it proved to be composed essentially of large glacial erratics. These are believed, in most cases, to have been derived from the wave-swept zone immediately above. As the land emerged, the boulders were dragged down in the undertow and lodged just below the level where the surf could move them. The relative absence of boulders between the shore and the barricade is also explained in part by the action of coast-ice, which floats off such boulders when the ice-foot breaks up. If the boulders happened to be dropped again just at the limit where, on account of the depth, the surf is no longer effective in moving boulders resting on the bottom, the erratics would further build up the wall constructed by the undertow. Very close to that limit of effective wave-wash, the winter-ice, because of the depth at which the boulders lie (submerged at high tide), would not be able to buoy up the heavy masses and float them away.

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[1] Proc. Bost. Soc. Nat. Hist., 1892, vol. 25, p. 464.

[2] Bull. Geol. Soc. Amer., 1894, vol. 6, p. 467.

If the land had, in postglacial time, ever been higher than to-day, erratics won from the wave-swept zone would have moved seaward beyond their present position through the operation of the causes just described. During a subsequent uplift of the land, the boulders could not, in any large number, be recalled to the new shore-line. The actual magnitude of the average barricade is certainly too great to warrant the belief that the waves would, under this condition, undo what they had, during the progress of elevation, accomplished. The character of the material making up the barricade and its organic relation to the wave-swept zone forbid, thus, the assumption of a secondary uplift following a former greater postglacial depression of the land than we now see.

One is forced to reject the idea that the barricades have been principally formed by 'longshore transport of boulders. The walls are developed very uniformly at the mouth and head, and along the sides of long bays. If they were the result of 'longshore deposition by floating ice, we should expect the accumulation of dropped boulders to be quite uneven, most pronounced where floes and pans most frequently strand, and, at other points, scarcely begun. It cannot be denied that coast-ice does carry boulders in this way, but one may justly question its ability to have performed so great an amount of work as that demanded in the construction of the barricades. For this hypothesis implies that the sea-floor along the broad track of the annual field-ice is peppered over with glacial erratics far greater in number than could have been furnished by the wave-swept zone, if that zone had had anything like the average proportion of the drift now seen above the highest shore-line.

Continuance of Elevation. — We cannot doubt that the elevatory process continues in both Labrador and Newfoundland. The almost universal belief of the old settlers on these shores is that in no other way can the changes in depth at familiar localities be explained. With no theory to support or refute, many reputable observers among the fishing population state that they have time and again noted, during periods of from thirty to sixty years, cases where rock-ledges have come perceptibly nearer the sea-surface, where new channels have had to be sought among the shoals for the passage of their fishing-boats, and where the stages must be again and again lengthened over their bed-rock foundations in order to secure a depth of water sufficient to float the small craft. Mr. Mark Gibbons, of St. John's, has made a study of the question for forty years, and has come to the conclusion that elevation is in progress along the whole coast. He believes that the rate of uplift is about twice as rapid in northern Labrador as in Newfoundland. He has found among the older settlements of the island some where the inhabitants are in a very unfavorable position for plying their industry on account of the rim of just submerged rock-ledges that obstruct the harbors. He has asked the older men why they chose such locations for settlement. The reply was that they or their fathers had made these harbors when the conditions were very different from the present, namely when the harbors were deeper. Such qualitative evidence, however great in amount, must yield in value to the testimony of even a few bench-marks carefully distributed along the coast. It is hoped that, with the co-operation of Bishop Marten of the Moravian church, of the missionaries under his charge at the various stations, of Dr. Grenfell and of Mr. Ford at Nachvak, a description may be published during the coming year of eight bench-marks fixed by these gentlemen. One of the stations is planned for northern Newfoundland.

The Scenery of the Emerged Zone. — The coastal landscapes exhibit many details which are those expected after the sea-bottom has been exposed by elevation. They figure among the most striking proofs of crustal movement.

Within the labyrinth of islands, wave-cutting has done little toward modifying the condition of the glaciated ledges. Outlying islands and headlands, as, for example, at Sloop (Brig) Harbor, Hopedale, Cape Harrison and Cape Strawberry, are usually very ragged and wave-worn throughout the wave-swept zone. The same contrast holds in the case of many individual islands which are uninjured on the landward side but strongly fretted on the seaward face. On the wooded hills of Great Bréhat and Cape Rouge in Newfoundland, where the slates and other sediments present relatively small resistance to sea-attack, the highest shore-line was the more easily determined because of the dissimilarity of the ragged zone of emergence and the smoother, erratic-covered zone. Benches and strong wave-cut cliffs, at all elevations up to the level of the highest shore-line, appear at almost every exposed point on the Labrador. An exceedingly picturesque sea-cliff occurs just above a 205-foot beach on Pomiadluk Point. Others were particularly noted on Cape Harrison, Cape Strawberry, at Sloop Harbor, at Ice Tickle, and at Aillik Bay.

Very rarely are the benches of great breadth or length; nor are they usually horizontal. They have been developed by rifting on gently curving master-joints. They are not the continuous, horizontal terraces of our text-book diagrams. The benches cannot be taken to mean so many halts during the process of elevation; but are rather determined in size, form, and position by the controlling planes of jointing.

Elevated sea-chasms, often located on trap-dikes, indent the cliffs in large numbers. The great length of some of these is quite extraordinary. A half mile northwest of the Mission House at Hopedale and at an altitude of 325 feet, a chasm three hundred yards in length has been worn out during submergence by waves that followed the trend of a trap dike. The vast majority of the fossil chasms are similarly located on trap dikes. The latter, with respect to subaerial destruction, may be hard in comparison to the country-rock and project above the highest shore-line as ridges; below that line the same dikes may prove less resistant to the attack of the waves than the country-rock and have thus served to locate chasms. Examples occur on the shores of Aillik Bay. The position of the highest shore-line is beautifully shown at the upper termination of a dike-chasm, still floored with rounded boulders, that forms a conspicuous landmark above the anchorage at Ford Harbor. Above the line, the surface of the dike is flush with the glaciated gneiss. The most picturesque chasm seen during the summer is one 250 yards long, 75 feet deep, and 20 feet wide that was found on Long Island, at American Tickle. The waves still reach nearly to the head of this chasm, which is still being slowly deepened.

The waste of the fossil cliffs is seen at the present day in the raised beaches and other boulder accumulations that also represent, in part, the rearranged drift that once lay scattered over the emerged zone. In Newfoundland and southern Labrador, these deposits are as a rule covered deeply under peat, which seems to prefer such graded slopes as a place for rapid growth. The form and location of the slope was, in such cases, used in connection with the natural sections of brook-beds to indicate the nature of the deposit. North of Hamilton Inlet, the lack of a vegetable cap has rendered the exposures extremely good and the study easy and rapid. (Plate **10**, a and b.) Perhaps the finest exhibitions of the beaches were seen at Sloop Harbor (altitudes measured 115, 140, 160, and 215 feet), Aillik Bay, Hopedale, Pomiadluk Point (at 55, 65, 230, 250, 260, 315, 320, and 335 feet), and Port Manvers.

The development of the beaches was naturally found to be a function of four conditions, the relative amount of drift on the shore, the amount of resistance offered by the bed-rock to wave-erosion, the degree of protection afforded by outlying islands or shoals against the ocean-swell, and lastly, the height of the beach above the sea.

Near Cape Porcupine and north and south of Paul's Island, two typical regions are seen where the drift seems to have been left by the ice-sheet in much greater amount than elsewhere on the coast. Consequently, the "beach" of other parts becomes a coastal plain at the Cape, or a huge sand and gravel spit in the lee of many an island near Ford Harbor.

In Labrador, the fossil shore-lines have repeated the process exemplified on the existing shore of eastern Newfoundland. The porphyritic granite of Greenspond is suffering but very slow attack by the waves, and the coast is there for many miles devoid of beaches. Approaching Change Island from the south, one is struck by the more advanced development of the shore-line as illustrated in the abundant pocket-beaches and barrier-beaches wrought out of the fissile slates, quartzites, and schists.

Lying well within the island-belt, the hills about Rogue's Roost, Quirk Tickle and Cutthroat Tickle possess comparatively few beaches. In the time of submergence, the outer islands bore the brunt of erosion by the waves; the enfeebled Atlantic waves were unable to damage seriously the bed-rock so that it should furnish an essential part of the beach material. Where beaches do occur in this situation, they are almost entirely composed of glacial erratics, — a constitution that goes far to explain the usual contrast of the higher and lower beaches. The latter are the better developed both as to size and to the degree of rounding which the erratics have suffered through wave wear. This contrast is natural, for the lower deposits are mainly made up of boulders and pebbles that have been derived from the upper part of the emerged zone, and thus have been longer in the mill of the surf than the materials earlier lodged farther up the slope. At the same time, the loss of bulk by attrition has not been sufficient to counterbalance the gain to the lower beaches produced by the winning of erratics from above.

On some of the sand beaches, dunes apparently fossil and dating from a lower stand of the land, were discovered at varying heights above the sea. These are especially large and numerous in West Bay just south of Hamilton Inlet. At Pottle's Cove (West Bay) a fifteen-foot pocket beach two hundred yards long has resting upon it a number of typical dunes; the top of one of these is forty-five feet above high water mark. A much larger area of dunes fifteen to twenty feet high, covers an extensive thirty-five-foot terrace on the south side of West Bay. The antiquity of the dunes is indicated by the thick vegetable cap that has long kept them stationary and in essentially their present form.

The settlements on the Labrador are largely confined to the graded terraces close to sealevel. Their accessibility, relatively smooth surface, and naturally sheltered positions, have determined the location of houses, fishing-stages, and the long lines of bawns on which the codfish are dried. The inevitable graveyard is always situated on a raised beach, for only there is there sufficient depth of loose material on the bed-rock.

True pocket-beaches could not be sharply separated from boulder and pebble deposits that have been formed on steep-to shores or in the lee of submerged rock-knobs in several fathoms of water. With the latter are associated the very common aggregations of boulders flooring the little rock-basins situated among the mammillated ledges of the emerged zone. In this record therefore, the term "beach" may, in certain instances, be arbitrarily used.

One of the commonest forms assumed by the shore-detritus, is that of the barrier-beach or of its relative, the tombolo or tying-on bar. Fine examples of these occur at Port Manvers and at the eastern extremity of Paul's Island. The settlers on the coast recognize that certain peninsulas have been formed by the tying on of rocky islands to the mainland; such islands of an earlier time are locally called "barred islands." The recency of the shore-uplift is well shown in the numerous fresh-water ponds lying back of raised barrier beaches. Their basins represent either true coastal lagoons or the depressions located on the landward side of submarine bars. Often a series of bars form, with the tied-on rock-islands, the rim of a pond. Examples can be found at Mauve Bay, Newfoundland, at Pottle's Cove, West Bay, at Ford Harbor, and at Black Island Harbor. In every case, the pond exhibits extremely little infilling with wash from the adjacent hills, nor has the growth of peat significantly diminished the size of the basin. The freshness of form corroborates in striking degree the other evidence that goes to show how lately the land has emerged from beneath the sea. Occasionally the bar is cut through by a stream that has thus destroyed the integrity of the basin lying back of the bar.

Not the least conspicuous features of the views obtained along the coast, are the fossil spits such as those at Jigger Island, Sandy Island, Ford Harbor, John's Harbor and in the vicinity of Nain. Tailing off with beautifully even slopes from a few hundred feet to more than a mile in length, the spits invariably lie on the lee side of the islands to which they are attached. In most cases they appear to be still growing on their points although the flanks may be strongly cliffed by the waves; sometimes a spit will form a continuous bar from one rock-island to another.

Finally, attention should be called to the largest single deposit occurring in the zone of emergence and the only relatively large example of its class of geographic form on this coast: the coastal plain north of Cape Porcupine. From the cape it stretches fifteen miles northwestward to Tub Harbor at the North of Hamilton Inlet. The plain averages nearly four miles in breadth. It is covered with a thick growth of scrub timber which does not conceal its well graded character. The upper limit of the plain surface was estimated from a distance to be about two hundred and fifty feet above the sea; thence the smooth slope descends to the straight cliffs now being driven back by the actively encroaching sea. The plain has apparently lost rather more than a mile of its breadth in this way. There was a comparatively long halt in the process of elevation when the sealevel was about thirty-five feet above its present position; at that time there was developed a distinct bench that is visible in West Bay. The plain is underlain by stratified sands, and clays in which there are embedded a great number of large boulders, including anorthosite from the interior. The bulk of these materials may doubtless be referred to the drift as their original source. Many small consequent streams have been extended down the slope of the plain and are now deeply entrenched beneath its surface. The finest sand-beach on the Labrador sweeps in a great curve along the present shore.

The clays of the coastal plain seemed to promise that in them, if anywhere on the coast, fossiliferous beds might be discovered; but, even after prolonged search, the hope was destined to disappointment. Nor was better success to be had when other deposits of the coast were examined. It may be that organic remains are truly rare in them, but the short time permitted for the investigation of the beaches could not at all warrant this as the final conclusion. The rich finds of Packard at Hopedale and on the coast to the southward, certainly point to the expectation that the Labrador Quaternary may some day afford data sufficient for a fruitful comparison with beds of the same age all about the north Atlantic.

The Need of Further Exploration.

One cannot leave the consideration of this huge field of research, the northeast coast of Labrador, without indicating some of the directions in which repaying investigation might be carried on. Packard said in 1891 that "the Labrador Peninsula is less known than the interior of Africa or the wastes of Siberia."[1] Since that time a harvest of new facts has been reaped by Low in connection with the Canadian Geological Survey, and the secrets have to some extent been told. Packard has himself done much to remove this stain on the banner of American geological and geographical enterprise, in the publication of his book, embodying as it does many original observations. Yet, in his account of the coast, he was forced to sketch in but the briefest fashion, that part of it which is by long odds the most interesting, the region north of Hopedale. It is probable that for many years it will be impossible for government surveyors to be called away from economically more important fields to make thorough exploration of the coast. That work seems marked out by nature for private ventures.

Escaping from the heat of an American or Canadian summer, the explorer of northern Labrador will find a bracing, health-giving climate calling forth strenuous and welcome exercise of body and mind. If he be particularly interested in geological structures and processes, he will find, in the lack of soil and forest-cover, most fortunate conditions for rapid observation. Using a steamer sheathed for ice-navigation, an exploring party might be on the ground in early July and, from one end of the coast to the other, rarely fail to find a snug harbor close to the important points of attack.

The Kiglapait is unmeasured, unmapped and absolutely unknown as to composition. The Kaumajet sediments, covering several hundreds of square miles, present important structural and stratigraphic problems. Their age is quite undetermined, like that of the stratified rocks at Aillik Bay, at Pomiadluk Point and at Ramah. The Torngats afford a field of operations which it will take many seasons even to reconnoitre. In the last mentioned range are the highest mountains on the Atlantic seaboard of America, unmeasured and almost entirely unnamed. It would be of much importance to fix the elevation of the highest postglacial shore-line in the interior of the peninsula as well as on the south coast, in Newfoundland, Cape Breton and across Hudson's Strait, where isolated observations have already been made. The gross imperfection of the government charts for the region north of Cape Harrigan is such that no just idea is given of the splendid fiords that indent the plateau. These should be sounded and mapped if the great fishing fleet is to find appreciable help in their arduous calling from those who can afford the leisure to do this necessary work. The Labrador should be mapped at least as carefully as the coast of northern Norway. With the mapping, detailed observations of value on the hydrography of the coastal waters could be carried on. The remarkable tides of Ungava Bay, the marine zoölogy of the coast, particularly the study of the jelly-fishes, the fixing of bench marks to show the rate of elevation on the coast, the study of the fossiliferous beds of the raised beaches, — these and other subjects of research await the explorers of the future.

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[1] The Labrador Coast, Preface, p. 5.

EXPLANATION OF PLATES.

PLATE 1.

The basalts and underlying sediments of the Mugford Series as exposed on the northwest side of Mugford Tickle. The basement of crystalline rocks is seen on the left. It disappears near the middle of the view in consequence of the strong flexure revealed in the attitude of the stratified rocks above. The cliff is about 1,800 feet in height where it rises above the exposed basement.

PLATE 2.

The unconformity of the Mugford Series and Crystalline Complex, at Cape Mugford; cliff here from 1,800 to 2,000 feet in altitude.

PLATE 3.

The Tallek, or southern arm of Nachvak Bay; view taken from the height of about 1,500 feet on the southern slope of Mt. Elizabeth. Mt. Idyutak on the left.

PLATE 4.

The highest cliff in the Tallek; the cloud-capped peak on the left is the summit of Mt. Idyutak, 3,400 feet in height; view taken at a distance of about one mile from the shore.

PLATE 5.

Glacial amphitheatre near Mt. Razorback, north of entrance to Nachvak Bay; looking north.

PLATE 6.

Hanging Valley of the Korlortoâluk, Nachvak Bay (see Plate 12); Mt. Elizabeth on the left, separated from Mt. Ford on the right by a glaciated col; this col is drained into the main hanging valley, which comes in from the right; looking north.

PLATE 7.

Glacial lunoid furrow, one foot from horn to horn, and an inch and a quarter in depth; found with many others on hornblende granite at Hopedale.

PLATE 8.

Wave-swept zone as represented in Bear Island, a granite knob cut by trap dikes; about 100 feet in height.

PLATE 9.

Boulder barricade at Ford Harbor; at half tide; looking east.

PLATE 10.

a. Elevated gravel beach and sand dune at West Bay, south side of entrance to Hamilton Inlet; beach 35 feet above high water.

b. Near view of boulder beach 100 feet above high water; west (lee) side of Brig Harbor Island.

PLATE 11.

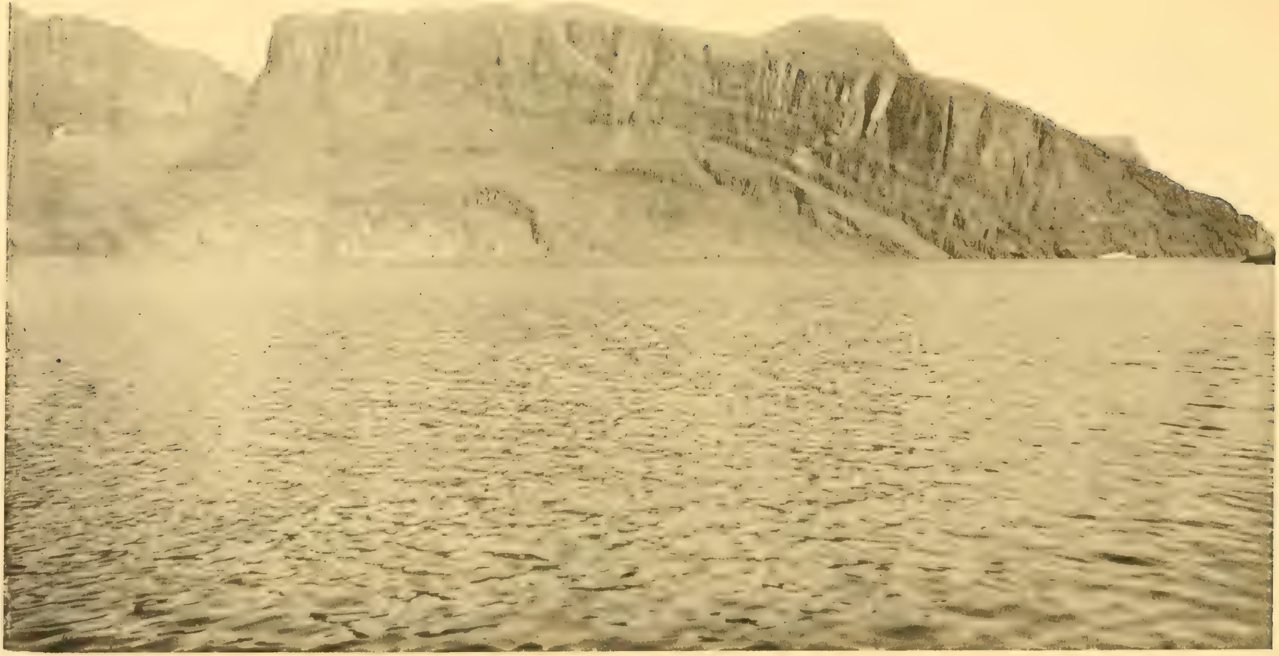
Sketch map of the northeast coast of Labrador, showing data concerning bed-rock geology. Heavy straight lines: observed strikes. Sinuous lines: average strike of contorted schists. Horizontal lining: Ramah series. Vertical lining: Mugford series. Solid black: Nain gabbros.

PLATE 12.

Sketch map of Nachvak Bay. Heights in feet; depths in fathoms.

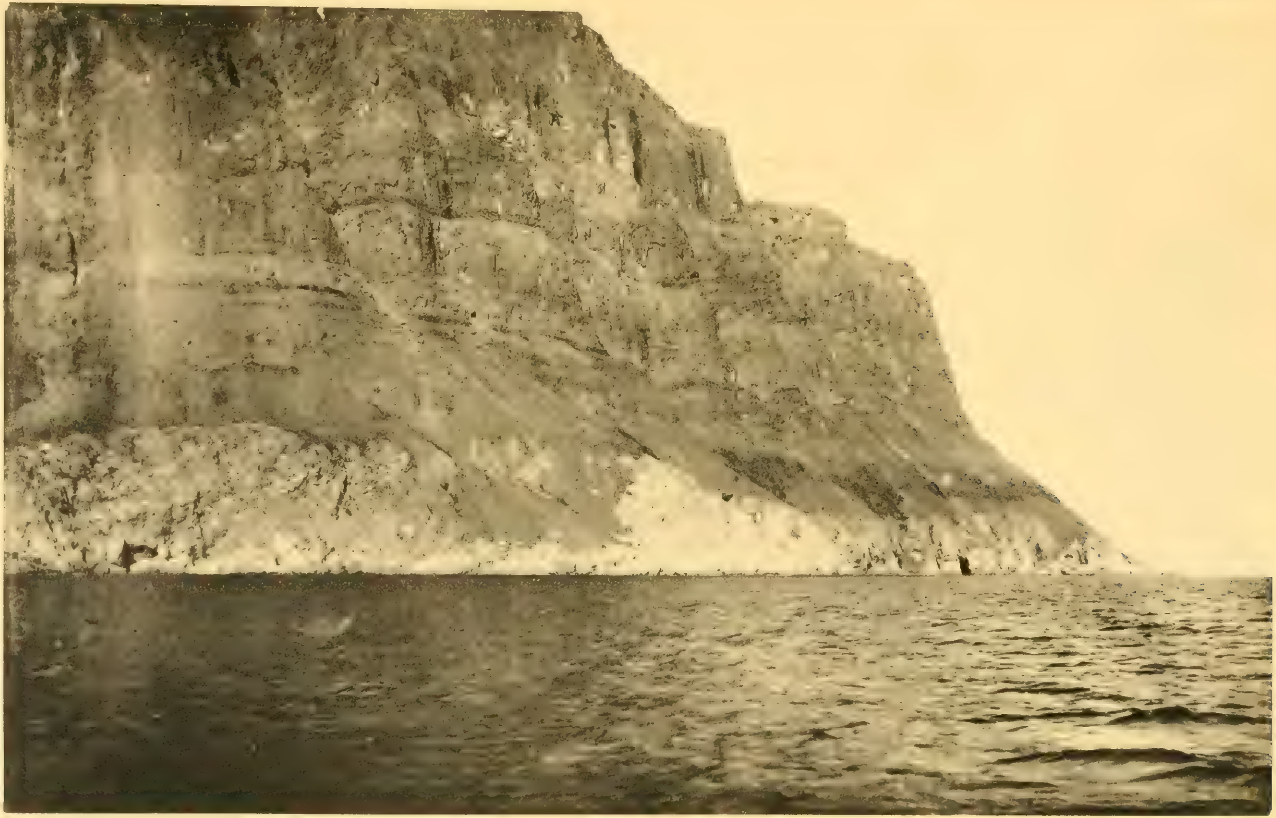
PLATE 13.

Sketch map of Newfoundland and part of the Labrador peninsula, showing data concerning glacial geology and postglacial elevation. Arrows indicate observed directions of glacial striae; numbers show local elevations of highest postglacial shore-line about present high water. (See Table III.)



HELIOTYPE CO., BOSTON.

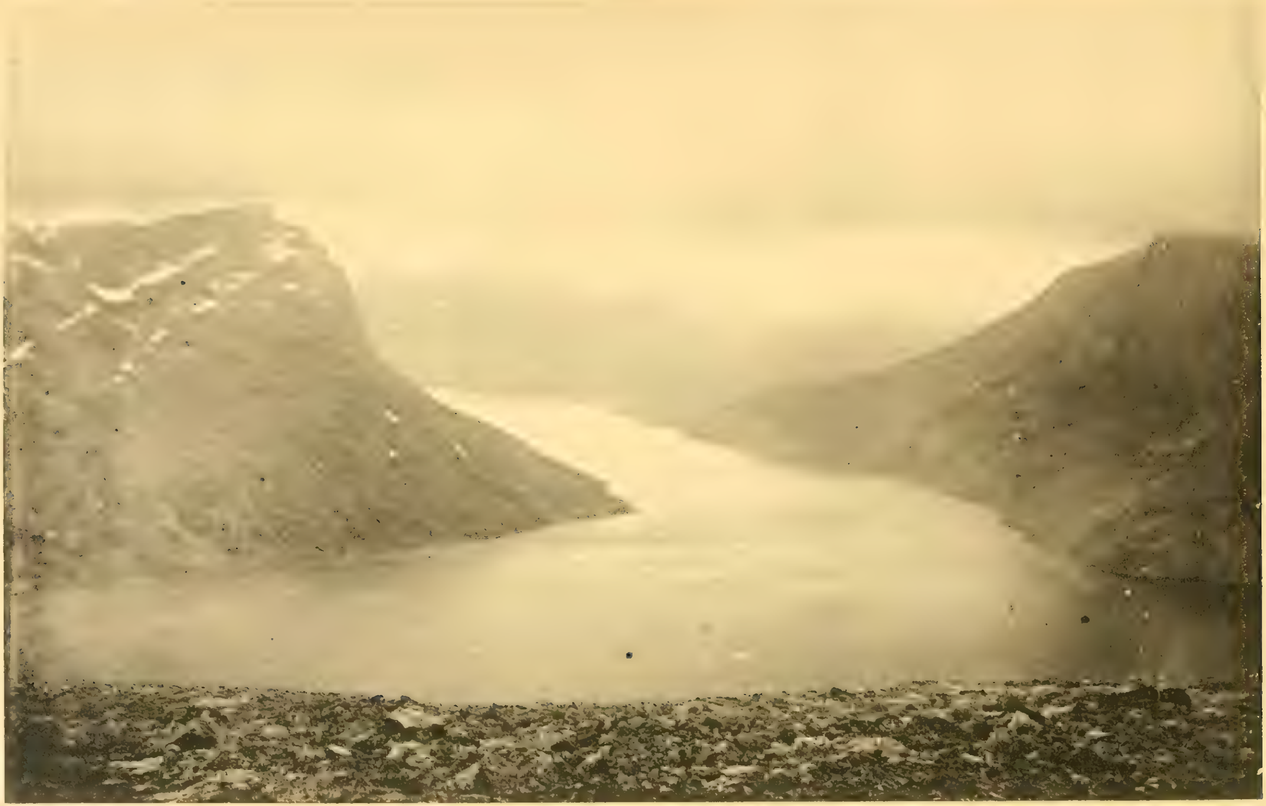
THE CLIFFS OF MUGFORD TICKLE.



HELIOTYPE CO., BOSTON.

CAPE MUGFORD.

Daly. Labrador. Plate 3.



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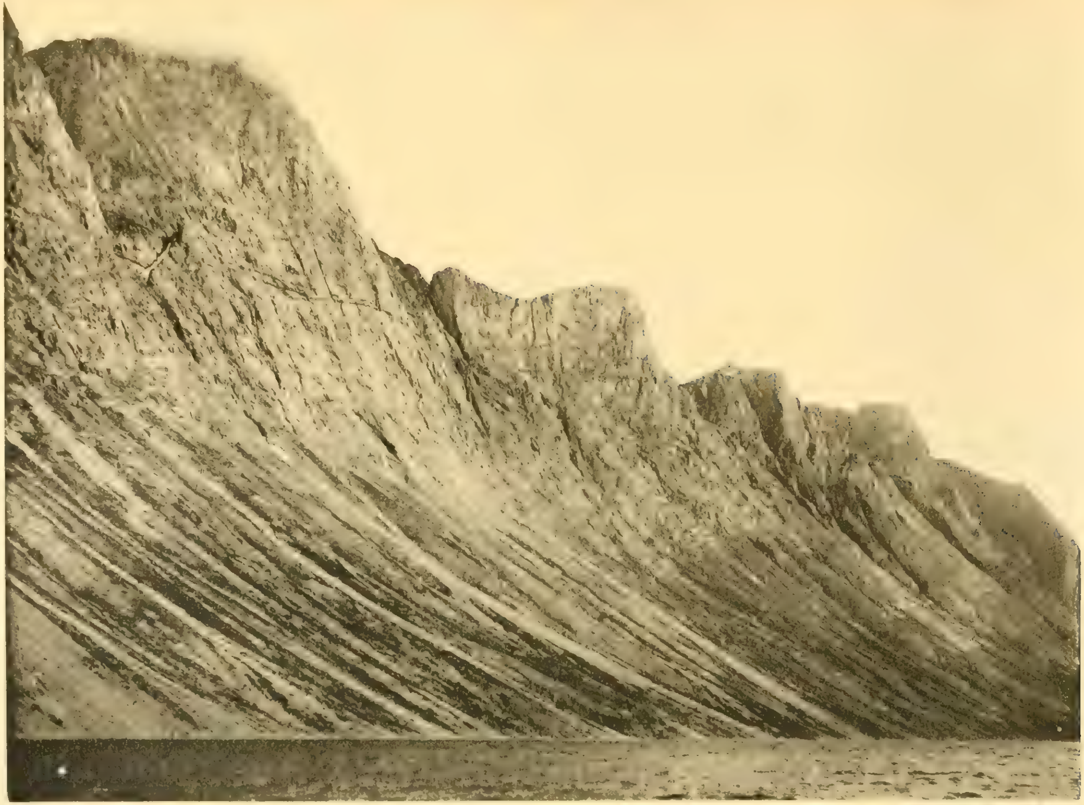
THE TALLEK, NACHVAK BAY.



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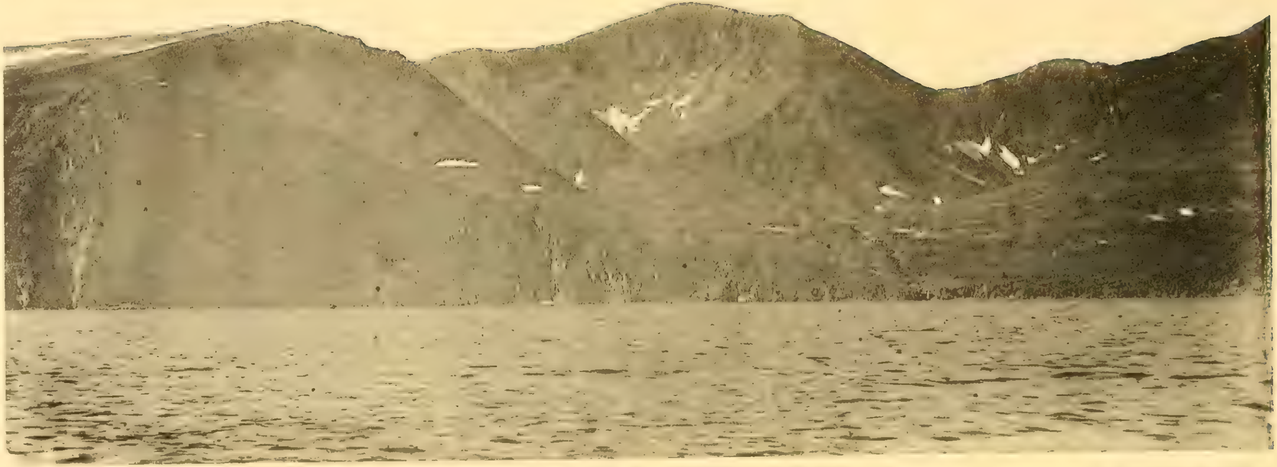
MT. IDYUTAK, NACHVAK BAY.



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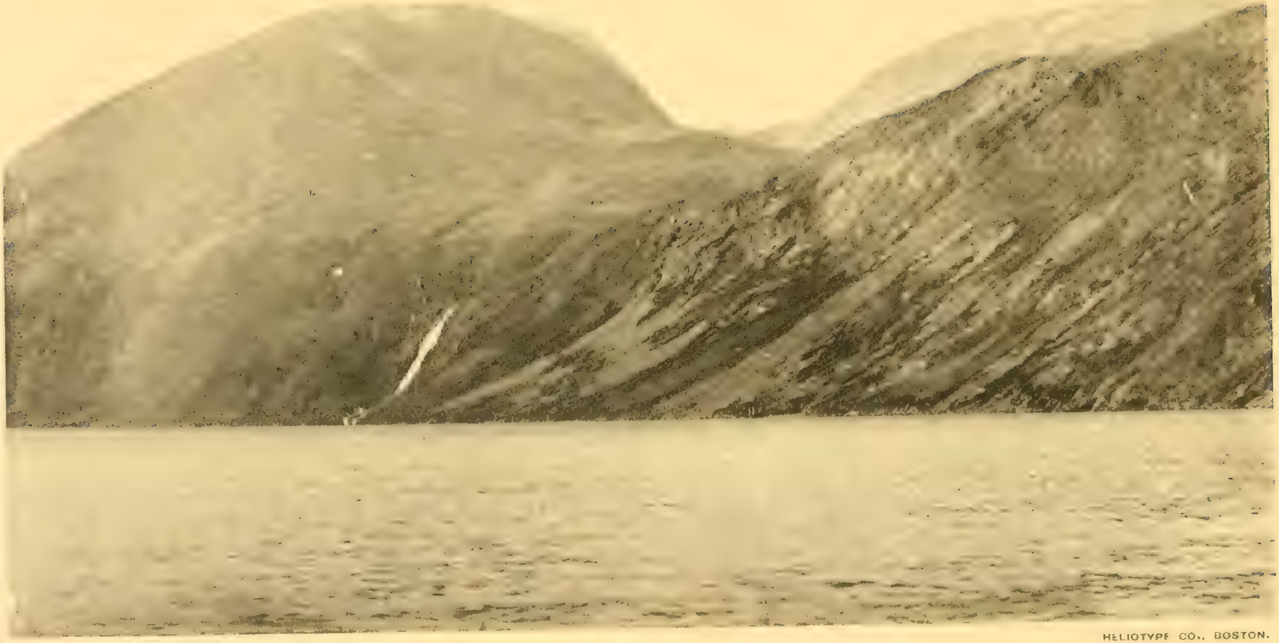
GLACIAL CIRQUE NEAR NACHVAK BAY.



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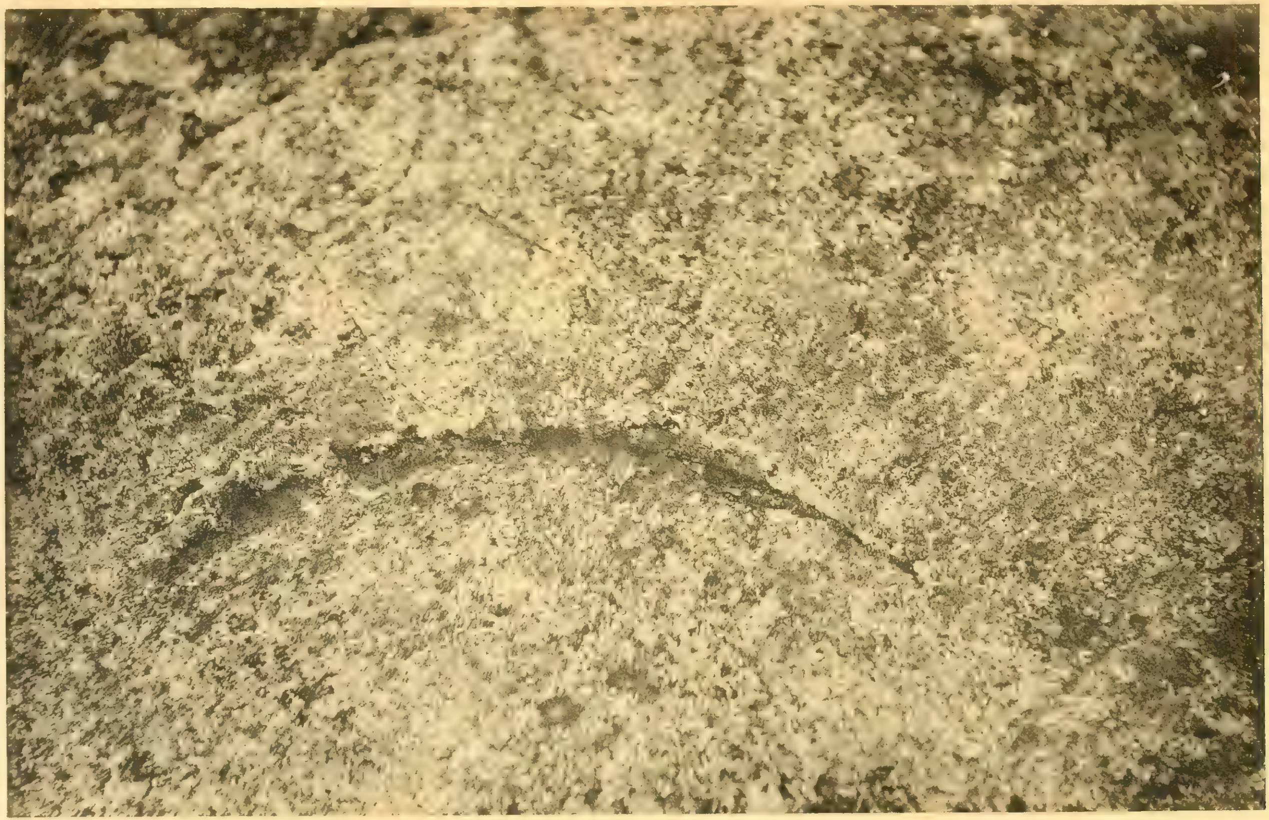
HANGING VALLEY, NACHVAK BAY.



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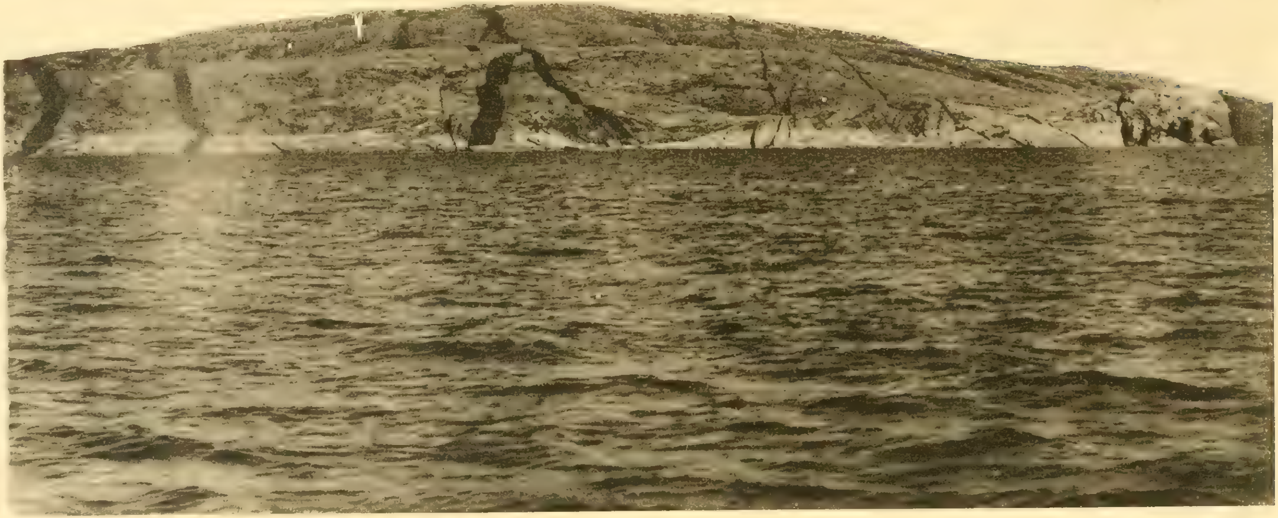
GLACIAL LUNOID FURROW, HOPEDALE.



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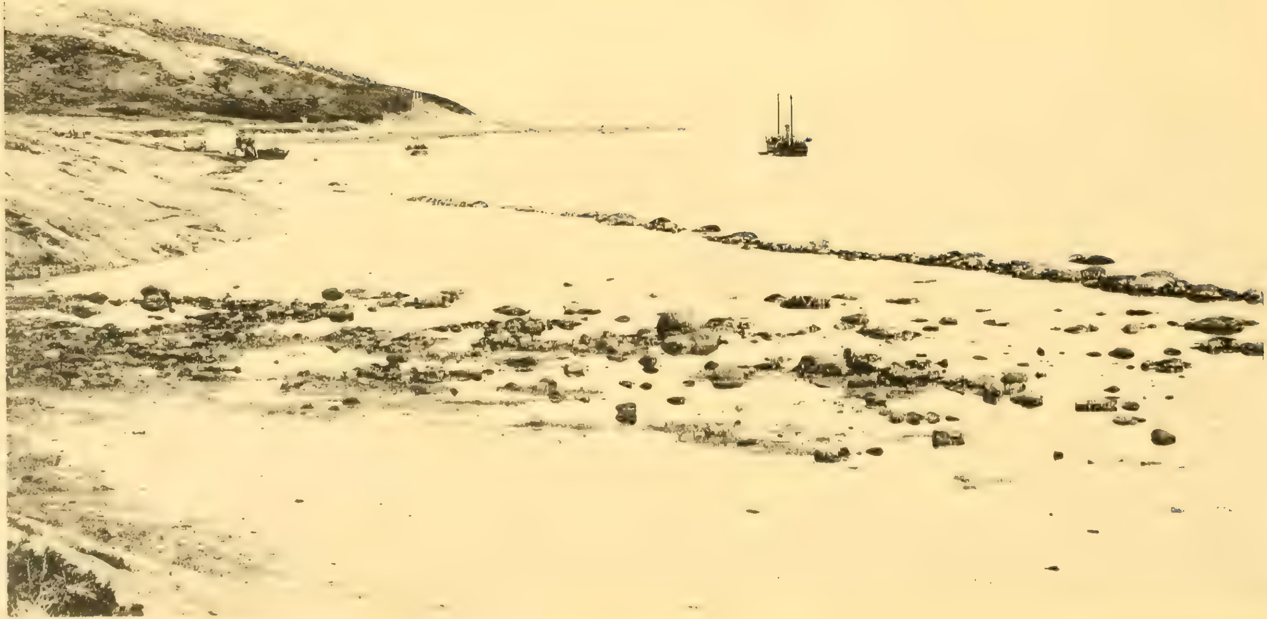
WAVE SWEPT ZONE, BEAR ISLAND.



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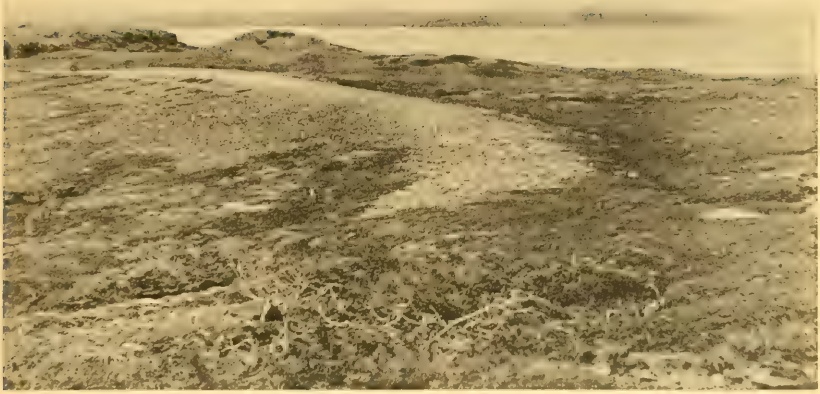
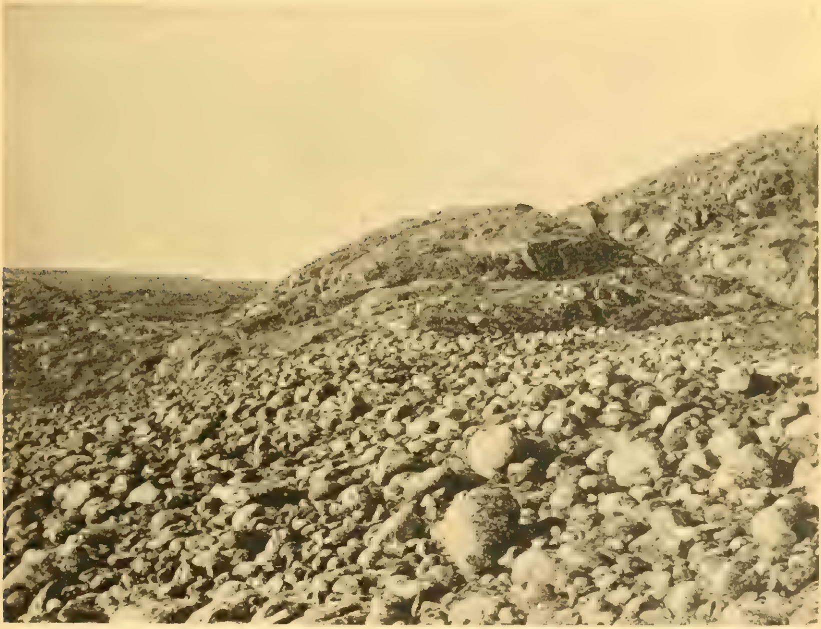
BOULDER BARRICADE, FORD HARBOR.



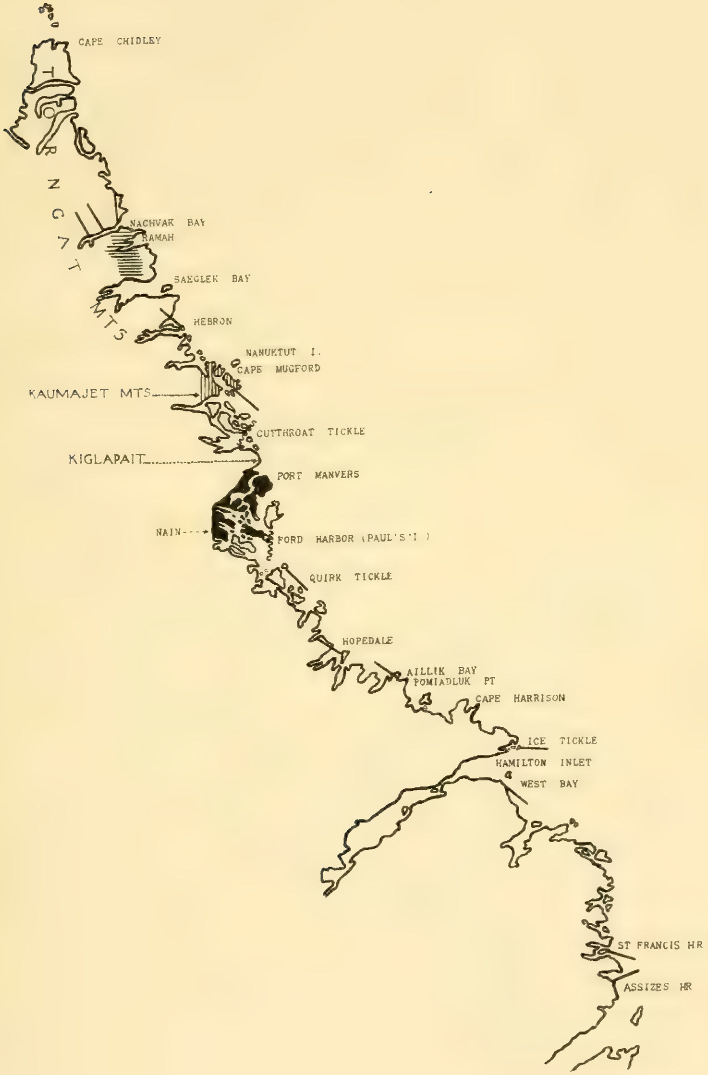
A.



HELIOTYPE CO., BOSTON.

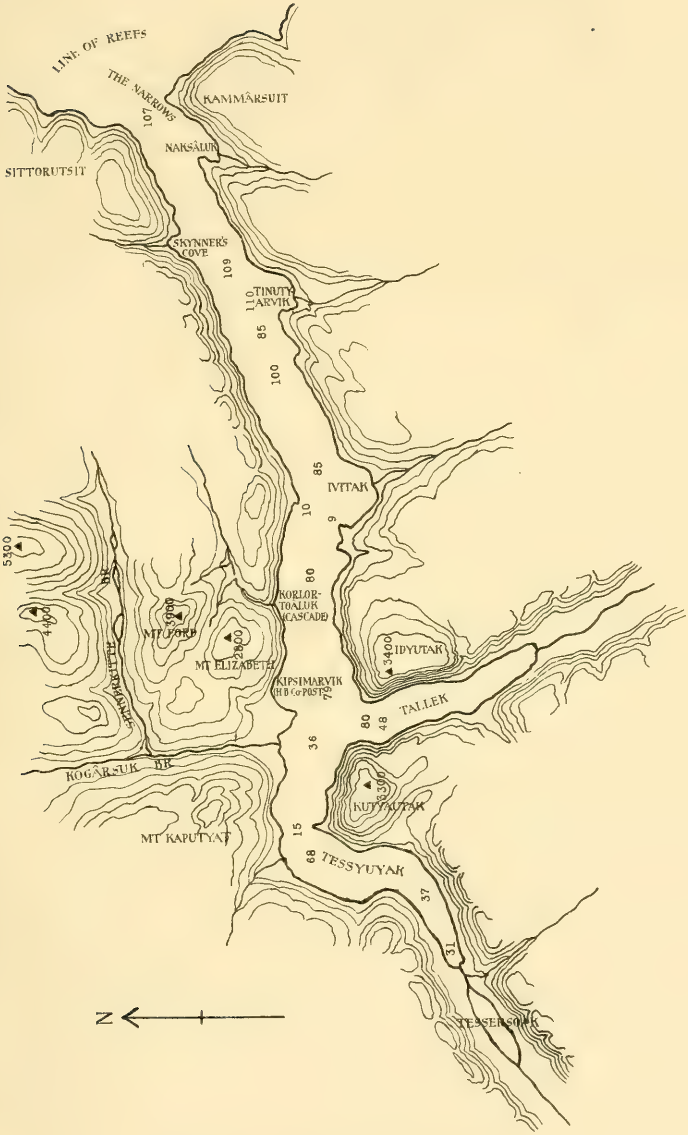
B.

RAISED BEACHES. A. WEST BAY. B. BRIG HARBOR ISLAND.


CAPE CHIDLEY
TORNGAT MTS
NACHVAK BAY
RAMAH
SAEGLEK BAY
HEBRON
NANUKTUT I.
CAPE MUGFORD
KAUMAJET MTS
CUTTHROAT TICKLE
KIGLAPAIT
PORT MANVERS
NAIN
FORD HARBOR (PAUL'S I.)
QUIRK TICKLE
HOPEDALE
AILLIK BAY
POMIADLUK PT
CAPE HARRISON
ICE TICKLE
HAMILTON INLET
WEST BAY
ST FRANCIS HR
ASSIZES HR

BED-ROCK GEOLOGY.

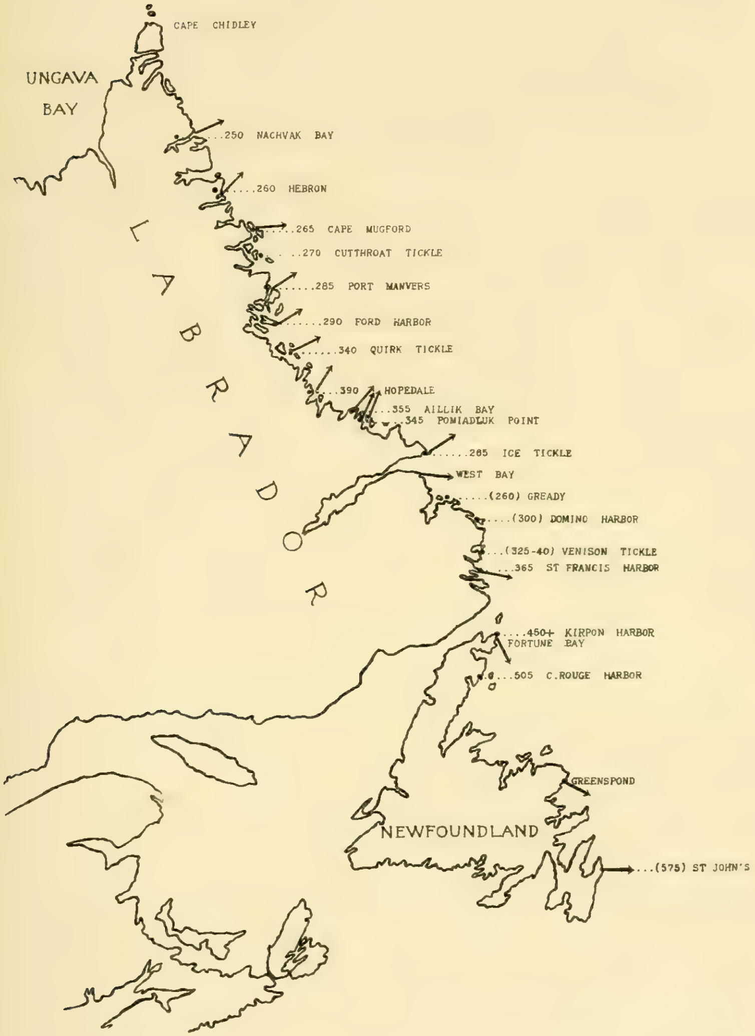
SCALE: 100 miles to one inch.


LINE OF REEFS
THE NARROWS
KAMMÂRSUIT
107
NAKSÂLUK
SITTORUTSIT
SKYNNER'S COVE
109
TINUTYARVIK
110
85
100
85
IVITAK
10
9
5300
4400
BR
3900
MT FORD
2800
MT ELIZABETH
80
KORLORTOALUK (CASCADE)
IDYUTAK
3400
KIPSIMARVIK (H B Co POST)
79
80
48
TALLEK
36
KOGÂRSUK BR
3300
KUTYAUTAK
MT KAPUTYAT
15
68
TESSYUYAK
37
31
TESSERSOAK
N

SKETCH MAP OF NACHVAK BAY.

SCALE: 6 miles to one inch.

Contour Interval: 500 feet.


CAPE CHIDLEY
UNGAVA BAY
...250 NACHVAK BAY
....260 HEBRON
....265 CAPE MUGFORD
...270 CUTTHROAT TICKLE
......285 PORT MANVERS
.......290 FORD HARBOR
.......340 QUIRK TICKLE
....390 HOPEDALE
...355 AILLIK BAY
...345 POMIADLUK POINT
LABRADOR
......285 ICE TICKLE
WEST BAY
.....(260) GREADY
....(300) DOMINO HARBOR
...(325-40) VENISON TICKLE
...365 ST FRANCIS HARBOR
....450+ KIRPON HARBOR
FORTUNE BAY
...505 C.ROUGE HARBOR
GREENSPOND
NEWFOUNDLAND
...(575) ST JOHN'S

GLACIAL STRIATION: POSTGLACIAL ELEVATION.

SCALE: 170 miles to one inch.

The following Publications of the Museum of Comparative Zoölogy are in preparation: —

Reports on the Results of Dredging Operations in 1877, 1878, 1879, and 1880, in charge of ALEXANDER AGASSIZ, by the U. S. Coast Survey Steamer "Blake," as follows: —

E. EHLERS. The Annelids.
C. HARTLAUB. The Comatulæ, with 15 Plates.
H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea.
A. E. VERRILL. The Alcyonaria.

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of ALEXANDER AGASSIZ, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander JEFFERSON F. MOSER, U. S. N., Commanding.

Illustrations of North American MARINE INVERTEBRATES, from Drawings by BURKHARDT, SONREL, and A. AGASSIZ, prepared under the Direction of L. AGASSIZ.

LOUIS CABOT. Immature State of the Odonata, Part IV.
E. L. MARK. Studies on Lepidosteus, continued.
" On Arachnactis.
R. T. HILL. On the Geology of the Windward Islands.
W. McM. WOODWORTH. On the Bololo and Palolo of Fiji and Samoa.
A. AGASSIZ and A. G. MAYER. The Acalephs of the East Coast of the United States.
AGASSIZ and WHITMAN. Pelagic Fishes. Part II., with 14 Plates.
J. C. BRANNER. The Coral Reefs of Brazil.

Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieutenant Commander Z. L. TANNER, U. S. N., Commanding, in charge of ALEXANDER AGASSIZ, as follows: —

A. AGASSIZ. The Pelagic Fauna.
" The Echini.
" The Panamic Deep-Sea Fauna.
K. BRANDT. The Sagittæ.
" The Thalassicolæ.
C. CHUN. The Siphonophores.
" The Eyes of Deep-Sea Crustacea.
W. H. DALL. The Mollusks.
H. J. HANSEN. The Cirripeds.
W. A. HERDMAN. The Ascidians.
S. J. HICKSON. The Antipathids.
W. E. HOYLE. The Cephalopods.
G. VON KOCH. The Deep-Sea Corals.
C. A. KOFOID. Solenogaster.
R. VON LENDENFELD. The Phosphorescent Organs of Fishes.
H. LUDWIG. The Starfishes.
J. P. McMURRICH. The Actinarians.
E. L. MARK. Brachiocerianthus.
JOHN MURRAY. The Bottom Specimens.
P. SCHIEMENZ. Pteropods and Heteropods.
THEO. STUDER. The Alcyonarians.
M. P. A. TRAÜTSTEDT. The Salpidæ and Doliolidæ.
E. P. VAN DUZEE. The Halobatidæ.
H. B. WARD. The Sipunculids.
H. V. WILSON. The Sponges.
W. McM. WOODWORTH. The Nemerteans.
" The Annelids.

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Bulletin of the Museum of Comparative Zoölogy
AT HARVARD COLLEGE.
VOL. XXXVIII.

GEOLOGICAL SERIES, Vol. V. No. 6.

LEUCITE-TINGUAITE FROM BEEMERVILLE, NEW JERSEY.

BY JOHN E. WOLFF.

CAMBRIDGE, MASS., U.S.A.:
PRINTED FOR THE MUSEUM.
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FEB [illegible]

No. 6.— *Contributions from the Harvard Mineralogical Museum*, VI.

Leucite-Tinguaite from Beemerville, New Jersey. By John E. Wolff.[1]

Introductory.

The post-Cambrian eruptive rocks of Sussex County, New Jersey, have been the subject of several interesting papers,[2] which have described the elaeolite-syenite and some of the associated rock masses (ouachitite), and several of the dikes, but not the rocks of the whole complex. In 1896 and other years the writer was engaged with the areal geology of this region and made rock collections from the old localities and from several new ones discovered in going over the ground; a list of which with map has been published.[3] He hopes to complete the description of this material, of which the present paper forms the first instalment.

Leucite-Tinguaite.

This rock occurs as a dike in the main mass of the elaeolite-syenite two miles northwest of Beemerville, and near the southwest end of the syenite. It was found in a field just under the 1300-foot contour of the topographic map and a short distance east of the road over the mountain. The dike is fifteen inches wide, cutting coarse syenite, with a strike N. 35 W. and dipping 45 northeast; it is exposed for but a few feet.

The rock has a dull greasy green color, is dense grained and contains distinct phenocrysts of nepheline in hexagonal prisms and large phenocrysts of pseudo-leucite, which weather white on the rock surface and are greenish white in the fresh rock; they have a diameter of fifteen centimeters at the maximum and occur in bands parallel to the walls of the dike. Their form is that of the leucite eikositetrahedron, the crystal forms rather perfect, and the outlines linear and sharp in cross section. The nepheline and leucite phenocrysts are evidently somewhat vicarious, for zones of the rock rich in one are poor in the other.

---

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] B. K. Emerson, Amer. Journ. Sci., 23, p. 302 and 376, 1882. J. F. Kemp, Amer. Journ. Sci., 38, 1889, p. 130; the same, Trans. N. Y. Acad. Sci., 11, p. 60, 1892; Amer. Journ. Sci. 45, 1893, p. 298; Amer. Journ. Sci., 47, 1894, p. 339.

[3] Geol. Survey N. J. Annual report, 1896, p. 91.

Microscopically the rock is composed of the following minerals:

Phenocrysts of nepheline and pseudo-leucite; few crystals of augite and occasional plates of biotite.

Ground mass: aegirine-augite needles, orthoclase, nepheline as essentials, with a little analcite, biotite, calcite, etc.

The nepheline phenocrysts are glassy and fresh, bounded by base and prism. The pseudo-leucites are composed of an aggregate of orthoclase, partly in irregular grains, more often in radiating prisms, forming even imperfect sphero-crystals, several of which may occupy one original leucite. Between the orthoclase there is a comparatively small amount of nepheline, usually in irregular patches, rarely in prisms, and this nepheline lies between the orthoclase rays. The space in the centre of the original leucite, especially that between the curving boundaries of two opposite spheroids of orthoclase is filled with a clear isotropic substance with refractive index lower than the feldspar, traces of cubic cleavage, gelatinizing with HCl, and determined as analcite. Into this the square ends of the orthoclase rays sometimes project with a structure curiously analogous to that described by Iddings ("Obsidian Cliff") in the obsidian spherulites, where rays of orthoclase project into a quartz or tridymite paste. Associated with the analcite there occurs an undetermined zeolite with equally low index, good double cleavage and distinct though feeble birefringence. The very early period of formation of the leucites is shown by their penetration by tongues of the rock carrying nepheline and augite phenocrysts.

The pyroxene phenocrysts are a deep green, slightly pleochroic, aegirine-augite, with the direction of negative extinction about 38° to c′. They sometimes have a centre of colorless or reddish augite and an aegirine border. Small masses of purple fluorite are deposited within or around them and they are frequently filled with secondary biotite. Associated with them are a few melanite crystals, titanite masses, areas of colorless fluorite and astrophyllite(?).

The ground mass comprises a fine net work of slender pyroxene crystals in a background of colorless minerals. These acicular pyroxenes are pale to deep grass green in color, slightly pleochroic, parallel c′ grass green perpendicular to c′ olive green; most of them extinguish nearly parallel to c′, others as high as 19°; in either case this is the negative optical direction and they would pass for aegirine or aegirine-augite. The colorless background is resolved in polarized light into irregular areas in which three elements occur. The most abundant is orthoclase, identified by its index of refraction lower than balsam, cleavages, and biaxial character; the analysis shows it can contain little sodium. Nepheline comes next, identified by its higher index, and lastly there are some isotropic areas of very low index with irregular cracking which are probably analcite.

A little biotite, calcite, fluorite, quartz, brilliantly polarizing cancrinite(?) and small areas of indeterminate zeolites are in insignificant amount. Grains of pyrite are scattered through the rock.

Analysis.

The analysis was made essentially according to the methods used by Hillebrand.[1] While it shows the general chemical characters of allied tinguaites, yet a striking difference is shown in the predominance of ferrous over ferric iron, combined with the high and nearly equal amount of the alkalies. The ferrous iron determination was made in duplicate by the hydrofluoric acid method, using a doubly tubulated bell-jar and sand bath instead of the water bath of Cooke (Pebal-Doelter method, see Jannasch, "Leitfaden der Gewichts-Analyse," p. 269), and the two determinations differed by only 0.02 per cent. The only mineral in the rock containing iron (except pyrite, which is separated in the tabulation, and a little biotite, etc.) is the pyroxene, and this is almost all in the ground mass where it has the optical characters of aegirine or aegirine-augite. A glance at the molecular proportions will show that there is an excess of the alkalies over the $(AlFe)_2O_3$ of 21 molecules and as there is no sodalite present it seems necessary to suppose this excess in sodium present in the pyroxene, where it must be combined in some way with ferrous and not with ferric iron, as would be the case were it aegirine. To better illustrate the difficulty, if we use *all* the ferric iron, with one sixth ferrous, and the proper soda for aegirine proper, distribute part of the remaining soda and the potash with the proper alumina and silica between nepheline and orthoclase, part of the ferrous iron with the lime and magnesia in the hedenbergite molecule, we will find with 3 per cent in the rock of aegirine, 13 per cent hedenbergite and 6 per cent of a compound $Na_2\overset{II}{Fe}(SiO_3)_2$. The investigations of Merian[2] and Mann[3] indicated that aegirine-augite contained sodium in some

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[1] **Bull. U. S. G. S., No. 176.**

[2] **N. J. Min. B. B., III. 1884, p. 252.**

[3] **N. J. Min. B. B., II. 1884, p. 172.**

	A	B	C	D	E	F	G
SiO_2	50.00	50.88	848	53.56	50.36	52.91	51.93
Al_2O_3 . . .	20.03	20.38	200	24.43	19.34	19.49	20.29
Fe_2O_3 . . .	0.98	1.00	6	2.19	6.94	4.78	3.59
FeO	3.98	4.05	56	1.22	. . .	2.05	1.20
MgO	0.69	.70	17	.31	. . .	0.29	.22
CaO	3.41	3.47	62	1.24	3.43	2.47	1.65
Na_2O	8.28	8.43	136	6.48	7.64	7.13	8.49
K_2O	8.44	8.59	91	9.50	7.17	7.88	9.81
$H_2O + 110°$	1.50	. . .	. . .	93	loss.	1.19	0.99
$H_2O - 110°$	0.10	. . .	. . .		3.51		0.10
CO_2	0.22	0.22	6	. . .	. . .	abs.	.25
TiO_2	0.99	1.01	12	. . .	. . .	abs.	.20
P_2O_5	0.21	0.21	1	. . .	. . .	trace.	.06
FeS_2	0.54	0.55	4	. . .	SO_3	= 0.52	= .67
Fl	not det.	. . .	. . .	. . .	. . .	. . .	0.27
Cl	trace.	. . .	. . .	. . .	. . .	0.53	0.70
MnO	0.50	0.51	7	0.10	0.41	0.44	trace.
BaO	abs.	. . .	. . .	. . .	. . .	X. 0.48	0.09
SrO	. . .	. . .	. . .	. . .	. . .	0.09	0.07
	99.87	100.00	1446	99.96	98.80	100.25	100.58 0 = .27
							100.31

Specific gravity, 2.701 at 20° C.

A. Leucite-tinguaite, Beemerville, by J. E. Wolff.

B. The same calculated to 100 water free.

C. Molecular ratios.

D. Elaeolite-syenite, Beemerville, by L. G. Eakins, Bull. U. S. G. S., No. 150, p. 211.

E. " " " by F. W. Love (Kemp, Trans. N. Y. Acad. Sc., Vol. XI. p. 60, 1892).

F. Leucite-tinguaite, Magnet Cove, by J. F. Williams, Arkansas Geol. Survey, Vol. III. p. 287.

G. Leucite-tinguaite, Bearpaw Mts., Montana, by H. N. Stokes (Weed and Pirsson, Am. Journ. Sc., II. p. 196, 1896).

other combination with ferric iron than as aegirine; the present case indicates some combination with ferrous iron as yet unknown, and of course purely hypothetical.

A rough quantitative mineral calculation of the rock gives:

Pyroxene, 22 per cent.
Nepheline, 36 per cent.
Orthoclase, 38 per cent.
Titanite, Apatite, etc., 4 per cent.;

the analcite actually present is excluded but would of course lower the percent of nepheline. Analyses D and E are introduced as the only published ones of the elaeolite syenite of Beemerville; the incomplete analysis E shows much similarity with the tinguaite. Analyses F and G of leucite-tinguaites differ mineralogically from the Beemerville tinguaite by containing sodalite.

It should be mentioned that J. F. Kemp (*loc. cit.*) has described two camptonitic dikes — six, and nine and a half miles respectively distant from the Beemerville dike — in which certain curious spheroids without definite crystal outlines and composed mainly of analcite are referred to original leucite, of which some traces are stated to remain.

Mineralogical Laboratory,
Harvard University, Jan., 1902.

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E. EHLERS. The Annelids of the "Blake."
C. HARTLAUB. The Comatulæ of the "Blake," with 15 Plates.
H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea of the "Blake."
A. E. VERRILL. The Alcyonaria of the "Blake."

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of ALEXANDER AGASSIZ, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

Illustrations of North American MARINE INVERTEBRATES, from Drawings by BURKHARDT, SONREL, and A. AGASSIZ, prepared under the direction of L. AGASSIZ.

LOUIS CABOT. Immature State of the Odonata, Part IV.
E. L. MARK. Studies on Lepidosteus, continued.
" On Arachnactis.
R. T. HILL. On the Geology of the Windward Islands.
W. McM WOODWORTH. On the Bololo or Palolo of Fiji and Samoa.
A. AGASSIZ and A. G. MAYER. The Acalephs of the East Coast of the United States.
AGASSIZ and WHITMAN. Pelagic Fishes. Part II., with 14 Plates.
J. C. BRANNER. The Coral Reefs of Brazil.

Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieutenant Commander Z. L. TANNER, U. S. N., Commanding, in charge of ALEXANDER AGASSIZ, as follows: —

A. AGASSIZ. The Pelagic Fauna.
" The Echini.
" The Panamic Deep-Sea Fauna.
K. BRANDT. The Sagittæ.
" The Thalassicolæ.
C. CHUN. The Siphonophores.
" The Eyes of Deep-Sea Crustacea.
W. H. DALL. The Mollusks.
H. J. HANSEN. The Cirripeds.
W. A. HERDMAN. The Ascidians.
S. J. HICKSON. The Antipathids.
W. E. HOYLE. The Cephalopods.
G. VON KOCH. The Deep-Sea Corals.
C. A. KOFOID. Solenogaster.
R. VON LENDENFELD. The Phosphorescent Organs of Fishes.
H. LUDWIG. The Starfishes.
J. P. McMURRICH. The Actinarians.
E. L. MARK. Branchiocerianthus.
JOHN MURRAY. The Bottom Specimens.
P. SCHIEMENZ. The Pteropods and Heteropods.
THEO. STUDER. The Alcyonarians.
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GEOLOGICAL SERIES, Vol. V. No. 7.

RIVER TERRACES IN NEW ENGLAND.

BY W. M. DAVIS.

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No. 7. — *River Terraces in New England.* By W. M. Davis.

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I. General Statement.

THEORIES OF RIVER TERRACES. The terraces carved by streams in the washed drift of our valleys have been frequently studied and described since the beginnings of geological investigation in New England. In nearly all cases more attention has been given to terrace pattern as seen in vertical cross-section than as presented in horizontal plan. The cross-section is usually represented as in Figure 1, in which the depth of the rock-floored valley is made greater than that of the new valley carved in the drift filling. A notable feature of such terrace sections is that the open space measured across the valley between the scarps of the low-level terraces is narrower than that between the scarps of the high-level terraces; and this fact has frequently given rise to the supposition that the volume of our streams to-day is less than that of the streams by which the high-level terraces were carved. It will however be shown from what follows that the characteristic cross-section of a terraced valley in which the river has not yet reached rock bottom exhibits few stepping terraces, and is fairly represented by Figure 2; while if stepping terraces are present a characteristic section, on which the most significant points for a mile or more up and down the valley are projected, would show that the base of many of the terraces is determined for short distances (ten to fifty feet) by a rock ledge, as in

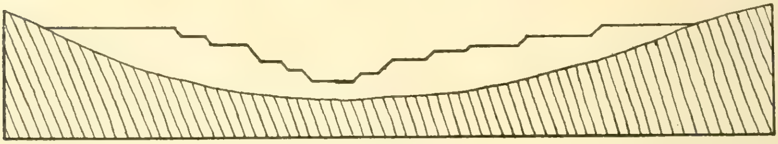

FIG. 1.

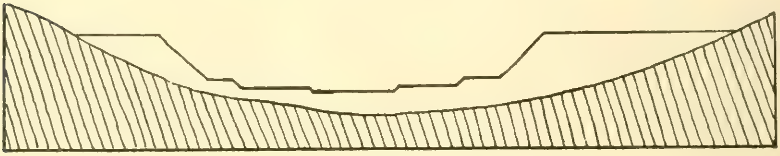

FIG. 2.

Figure 3, or better in Figure 4. This factor in the development of terraces was first recognized, as far as my reading has gone, by Hugh Miller (the younger), whose view will be presented in abstract on a later page.

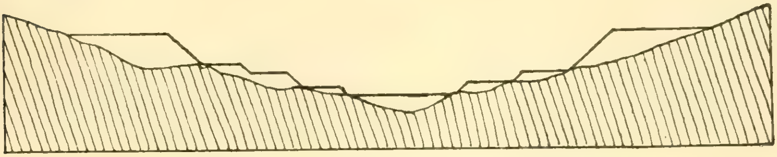

FIG. 3.

Although the controlling ledges occupy a very small fraction of the terrace length, they are of dominant importance ; and there can be little doubt that the finest flights of stepping terraces in New England are to be thus explained. Terraces of the kind shown in Figure 5 are different from those here studied, as will be more fully stated in the next section.

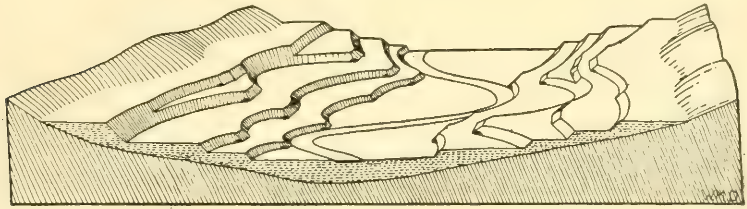

FIG. 4.

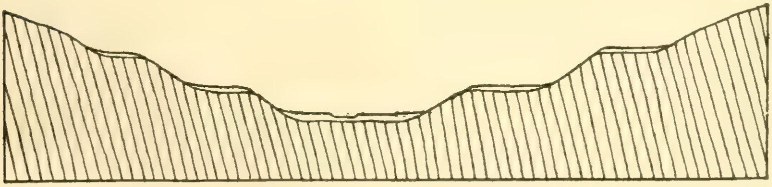

FIG. 5.

When the terrace pattern is considered in plan as well as in cross-section, it appears that our terraces may be accounted for, first, by the behavior of a meandering and swinging stream, slowly degrading a previously aggraded valley without change in volume; and, second, by the control exerted here and there over the lateral swinging of the stream through the discovery of rock ledges, as suggested by Miller. The following pages are devoted to a fuller consideration of this conclusion.

II. Preliminary Inquiry.

VARIOUS KINDS OF TERRACES. For the sake of clearness it is desirable to exclude at the outset all kinds of terraces other than those here studied. The terraces that occupy so many of our valleys are known as river terraces, drift terraces, or alluvial terraces. They have as to origin nothing in common with the terraces of sea-shores, such as occur on the coastal slopes of Cuba; or with the lake-shore terraces so well developed in the basins of Bonneville and Lahontan. They bear little resemblance to structural rock benches, such as break the slopes of valley sides in dissected plateaus, as in West Virginia or on a still larger scale in the Colorado canyon. They have little likeness to the silt and gravel-covered rock terraces formed when a graded river, revived by uplift, cuts a new valley in its former valley floor, as along the gorge of the Rhine on its way through the Schiefergebirge of western Germany.

Our New England drift terraces have a flat and nearly level upper surface or plain, limited backwards by rising ground and forwards by falling ground, and to that extent they resemble the terraces of all the classes above mentioned; but they have certain well-marked features of their own. They are evidently the river-carved remnants of a body of stratified clays, sands, or gravels that once occupied in larger volume than to-day the rock-floored valleys of still earlier origin. Their upper surface, the terrace plain or floor, slopes with the fall of the stream by which their scarped face or front has been eroded; and in this they differ from sea and lake shore terraces and from structural rock benches, none of which have any particular relation to the slope of neighboring streams. They consist of unconsolidated, stratified drift; if a ledge appears in any part of a drift terrace it is manifestly an accidental element, although as will be shown it may exert a controlling influence on the pattern of the terrace front; in this our drift terraces differ from the structural rock benches of valley sides in dissected plateaus, and from the rock terraces that represent the former valley floors of revived rivers, both of which consist essentially of rock, even though the latter may bear a veneer of river drift on their surface, as in Figure 5. Moreover, drift terraces are in nearly all cases developed with much more irregularity of pattern than is the case with the terraces of other kinds. A single drift terrace — unless it be the highest one of a series — is seldom traceable many miles along a valley side; its length may be only a few hundred yards. Terraces of other kinds are usually much more persistent.

Our drift terraces differ, furthermore, from other terraces in the place that they occupy in the geographical cycle. They are not products of normal erosion during an undisturbed still-stand of a land mass, but are the consequence of some relatively short-lived episode during which a greater or less departure is made from the normal progress of a cycle. The terraces of New England occupy well-opened rock-floored valleys of earlier origin, and thus imply the previous attainment of maturity in the cycle which witnessed the development of our hills and valleys. The glacial period witnessed certain modifications of the preglacial valleys and closed with the accumulation of abundant drift in them, as well as with certain changes of level by which the rivers were prompted to wash the valley drift away. Postglacial time has allowed the rivers to enter well upon this task : yet, even when the task has been completed, the normal cycle of erosion in New England will not have advanced far beyond its preglacial phase; so brief are the glacial and terrace episodes compared to the time required for baseleveling a region of resistant rocks.

Systematically considered, river terraces may be best associated with the forms assumed by the waste of the land on the way to the sea. Flood plains and alluvial fans are representative examples of the form assumed by land waste while it is stopping on its way down a valley. Terraces are examples of the forms assumed by waste that still remains in its stopping-place after part of its volume has been swept forward again.

TERRACE PATTERNS. Before entering upon the consideration of the process of terracing it will be well to examine briefly the more characteristic elements of terrace pattern, especially as seen in horizontal plan. The plain or floor of a drift terrace frequently presents a rapid variation in width, usually terminating in points at its up and down stream ends, as in Figure 6. The borders are prevailingly formed of curves of greater or less length, but of tolerably uniform radius, concave to the stream and frequently uniting in cusps. When several cusps are grouped, one back of the other, so as to form a strong salient, they may be called a terrace spur. Convex borders fronting the stream occur but rarely.

The highest plain of a flight of terraces backs against the ascending slopes of the older valley side and accepts their outline as its border, as in Figure 6; while each lower terrace, as well as the existing flood plain — the "intervale" or "interval" of New Englanders — backs against the scarp of the next higher terrace; thus the intermediate members of a flight of terrace steps possess similar but not necessarily parallel outlines, front and back; the cusps between the curves all point towards the stream. The back border of a terrace is frequently followed by a marshy channel from which the terracing stream has been withdrawn by a short-cut or cut-off (as is more fully considered below) before the channel was filled; terrace plains thus characterized may slope gently away from the axis of the valley towards their back border, and if they are of moderate breadth the backward slope may be a relatively conspicuous feature, as in the lower terrace in the middle of Figure 6. Terrace of this kind were called "glacis terraces" by Hitchcock (58).[1] They are of very common occurrence, and serve to show that the sudden withdrawal of the terracing stream from a roundabout channel to a more direct course has not been unusual.

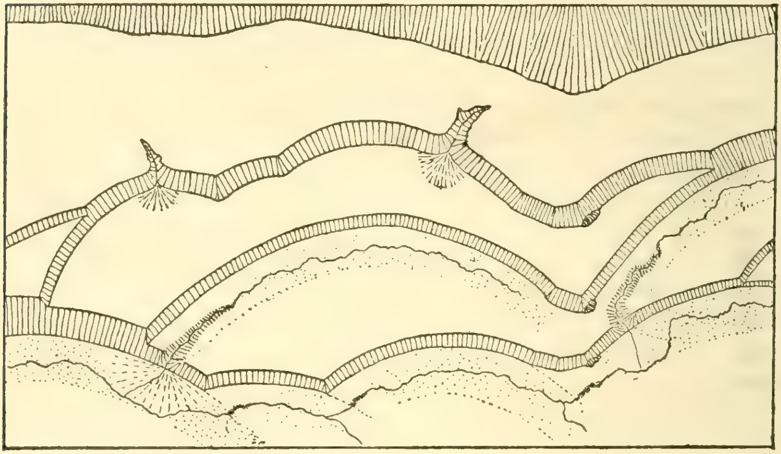

FIG. 6.

The scarp of a terrace connects the front border of the plain above with the back border of the plain below. Its sloping surface therefore presents a succession of curved re-entrants, separated by salients of greater or less acuteness. It is well known that the curved terrace fronts have been carved by the successive encroachments of a curved stream which once swung against their base, and that the stream has swung laterally at least as many times as there are terraces; but the behavior of the swinging stream has seldom been traced in detail.

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[1] Numbers in parentheses after an author's name are page references to his writings, cited in the Bibliography.

Although the plain and the descending scarp at its front are usually taken together as bounding a terrace, these two surfaces are not genetically connected in river terraces as they are in constructional lake-shore or delta terraces. River terraces being of destructional origin, it is the ascending scarp at the back of a terrace that should be associated with the plain beneath and in front of it. The line along the re-entrant edge between the plain and the ascending slope at its back is the most significant of all terrace lines. The front line of a terrace plain is of less significance, for it is determined merely by the slipping of the sands and clays down to the line of the undercut scarp at the back of the next lower terrace; the front line of a terrace plain is therefore of value only in so far as it represents the back line of the next terrace beneath.

Terrace scarps are steepest where the cutting stream has most recently swung against their base. In a series of stepping terraces, the youngest and steepest scarps are at the bottom of the flight; but when all the terraces of intermediate levels are destroyed by a chance lateral swing of the stream so that it undercuts even the highest terrace plain, then the whole descent from highest to lowest level may be fresh-cut with sharp edges at top and bottom. In older terraces, the scarps weather to a gentler slope, and the edges are rounded off. A convex slope of erosion is thus formed above and a concave slope of deposition below. The older the terrace, the greater the part of its front is occupied by rounded slopes and the gentler is the slope of the shortened tangent between them. At the same time, the salients or cusps between the re-entrants of the scarps as seen in plan lose their original sharpness of definition and become blunt and dulled. There has been no attempt to show details of this kind in the accompanying diagrams.

Gulches are often worn in terrace fronts by wet-weather streams, and fans are spread on the terrace plain below. The abandoned stream channels at the back border of a plain are usually taken as guides for surface drainage, whose gathered waters dissect the plain where it is cut off by the next lower terrace. A rather systematic drainage pattern is thus developed, as in Figure 6.

The several theories by which terraces have been explained may now be reviewed.

TERRACES CARVED BY STREAMS OF DIMINISHING VOLUME. The primitive explanation of terraces is that the whole space between the upper terrace scarps represents the channel of a huge river by which the valley was once drained, and that successive diminutions of volume to that of the present river are indicated by the decrease of breadth between the terraces in descending order. Although this view has sometimes received distinguished advocacy, it has never gained general acceptance among geologists or geographers. It has, however, been very generally supposed that the present rivers are much smaller than they were when they began the work of terracing; hence it is desirable to consider the special features that should appear if a decrease in stream volume had actually taken place.

The best indication of the volume of the stream by which a terrace has been carved is afforded by the curvature of its frontal scarp. If the scarps of the low-level terraces have a radius and an arc of curvature similar to these elements in the existing river meanders, and significantly smaller than in the high-level scarps, while curves at intermediate levels show intermediate values, a diminution of stream volume may be fairly inferred. If the radius and arc of curvature are of about the same measure in the three cases, no change in stream volume is indicated.

On the other hand, if a stream were charged with abundant and coarse load in the last stages of its aggrading action, as seems to have been frequently the case in New England, its slope must have been relatively strong; and a graded river with a heavy load on a strong slope does not develop curves of as small radius as it would when subsequently flowing with the same volume but with a finer load on a gentler slope; hence a large radius of curvature in the uppermost terraces should not alone be taken as an indication of large volume; large arc of curvature should also be found before large volume is inferred. It is for this reason that some of the uppermost terraces of the Connecticut and the Westfield rivers, whose scarps seem to sweep in curves of greater radius than do those of the low-level terraces, cannot alone give assurance of a former greater volume for their rivers.

It is, however, rendered very probable by what is known of the later stages of the glacial period that many of our streams had greater volume then than now. The most effective cause for greater volume was the constraint of the ice sheet, whereby the drainage from the basins of north-flowing rivers was turned over the divides into the valleys of south-flowing rivers. This may have been the case while the ice still covered the northern basins, their waters (as far as they had any) then running as subglacial streams, which may have been forced to ascend slopes and cross divides. Effective constraint may also have been provided after the ice had at least in part withdrawn from the northern basins, but when it remained in sufficient force to obstruct their normal outlets, thus forming lakes whose overflow ran across a pass in the divide to some southern valley. Another cause for increased volume of our south-flowing rivers was the importation into their basins of a considerable snowfall that was received on the ice sheet over some northern basin. A fourth cause for increased volume of our rivers lies in a possibly greater precipitation during the later stages of the glacial period than at present. A fifth cause lies in a relatively rapid melting of the retreating ice sheet. It is eminently possible that these various causes may have contributed effectively to an increase in river volume while the New England valleys were aggrading with drift; but it does not follow that volumes decidedly larger than those of to-day were continued into the period of terracing.

Except where direct evidence is given by curvature and arc of high-level terrace scarps, a formerly greater volume of the terracing streams should be regarded only as a possible, not as an actual occurrence. It is especially desirable that large bulk and coarse texture of terrace deposits should not be too readily accepted as evidence of former greater volume of streams; for bulk of deposits is a function of time as well as of rate of action, and texture is a function of slope as well as of stream volume and velocity. Hence until time and slope are shown to have been insufficient to account for bulk and texture of deposits, it is not compulsory to account for them by greater stream volume.

Even if decrease of volume has been of general occurrence during the period of terracing, it has nevertheless not been in control of terrace development; for if it had been, stepping terraces should be much more abundant than they are to-day. As a matter of fact, the diagrams by which terraced valleys are ordinarily represented give an exaggerated idea of the prevalence and perfection of these graceful forms. It is rare to find a long flight of stepping terraces on both sides of a valley; it is rare to find a flight of terraces continued for any long distance along a valley side; when more than three or four low steps are to be counted, it is usually only for a moderate fraction of a mile that they persist. A large part of the length of our terraced valleys is bordered by a few terraces of strong scarps, or by a high terrace with one or two lower ones beneath it; and it is not uncommon to find at least one side of a valley enclosed by a single scarp in which the whole descent is made at once from the highest terrace plain to the lowest. If terracing had been due to a general decrease in the volume of our rivers, stepping terraces should be much more prevalent, and broad flood plains between the high scarps of a single terrace on each side of the valley should be much more rare than they are; and when the whole descent from high terrace to flood plain is made in a single scarp on one side of the valley, stepping terraces with broad treads should be well developed on the opposite side; but no such arrangement of terrace form can be said to prevail. Decrease of river volume must therefore be at most a subordinate cause of terracing, if, indeed, it is not as a rule a negligible factor in their production.

This conclusion seems to have been clearly in the mind of Adams, state geologist of Vermont, who in 1846 wrote as follows: "The first stage in the process in which the terraces originated, the deposition of the materials, we have before referred to the older pleistocene. The process of denudation must have next followed, when the rivers, cutting down their channels through the drift barriers, lowered them gradually above the barriers. Flowing through the level deposits of sand, they must have formed serpentine channels, as rivers do now in alluvial plains; consequently by increasing the convexity of the bends, and then cutting them off or wearing away their headlands and shifting their beds, they would be meanwhile removing the greater part of the materials thus disturbed. By this process the greater portion of the original plain must have been carried off, and it is not necessary to suppose that the distance between opposite terraces is any indication of greater magnitude of the river, but only of its shifting its channel" (145, 146).

TERRACES CARVED BY STREAMS OF INCREASING SLOPE. When the basin of an aggrading river system is slightly tilted it may be expected that those streams whose slopes are decreasing will aggrade their valleys more rapidly than before (unless their point of junction with a degrading stream may be lowered more than their headwaters are depressed by tilting); while those whose slopes are increasing will change their action from aggrading to degrading. It is well known that New England has suffered a differential elevation in postglacial time. The postglacial clays of Lake Champlain and of southern Maine were deposited when the sea stood three hundred feet or more above its present level. The clays of the Connecticut valley in Massachusetts were, according to Emerson, deposited in lakes or bodies of slack water at or very close to the sea-level of their time, but the clays now reach elevations approaching two hundred feet. No postglacial changes of level of such amounts are known to have taken place along the southern New England coast. Our south-flowing rivers have therefore been accelerated, while those flowing northward have been retarded; and to this differential tilting Shaler has ascribed the weak terracing by streams of the latter class in contrast to the active terracing by those of the former.

While it is thus made very probable that the erosion of valley drift was determined by the unequal elevation of New England in postglacial time, it does not follow that individual terraces are in any close way related to this movement. Several cases must be here distinguished.

The northern uplift may have been accomplished in a single movement and so rapidly as to have revived the streams to an unusual activity of erosion, whereby they deepened their valleys quickly for a time, and did not begin to swing laterally, in the manner essential to terracing, until they had developed new grades of gentle declivity after the rapid uplift had ceased. In this case only a single high-level terrace and no intermediate terraces would be formed, and there would be but few low-level terraces.

A second supposition includes cases of repeated rapid uplifts separated by deliberate pauses, each of which would produce a result similar to that of the previous case. Here we should expect the river to have swung laterally at as many different levels as there had been pauses during the total uplift; and the flood plain formed during each pause would be of relatively persistent occurrence down the valley. But in order to protect the terrace remnants of the successive flood plains from being consumed by the river when it swings from side to side at lower levels, it is necessary to postulate that the movements of uplift should succeed each other at shorter and shorter intervals, so that the later-carved flood plains should be narrower than the earlier ones. The chief objection to this supposition is not so well directed against the postulate just mentioned as against the requirement of correlated levels in the terrace on the two sides of a valley. Such correlation is occasionally found, but it is by no means characteristic of our terraced valleys in general. The terrace levels are usually so discordant on the opposite sides of a valley that they cannot be considered the records of still-stands of the land between times of rapid uplift.

A third supposition considers an uplift so slow that the south-flowing rivers were never much accelerated; for during slow uplift the larger rivers might continue to swing actively from side to side, while all the time degrading the valley floor. In this case terraces might be cut at many different levels on opposite sides of the valley, according to the habit of the river in its lateral swinging.

The third supposition seems most appropriate to New England, for all of our valleys in which terraces are well developed exhibit flood-plain remnants at many levels, high and low, and neither so few in number nor so accordant in relative altitude above the river as to imply that lateral swinging had occurred only during the quiet intervals between rapid uplifts. But it should be noted that this conclusion applies better to the valleys of good-sized streams or rivers than to those of small brooks; for the latter frequently show only faint terraces or no terraces at all, even though they are branches of rivers whose valleys are well terraced. This seems to mean that an uplift which was so slow that a good-sized river could easily keep pace with it by down-cutting, may have been too fast for such a result in the case of a small stream. While the able-bodied rivers may thus have been always effectively at grade, leisurely swinging from side to side and at the same time slowly wearing down their valley floors, the small streams may have been for much or all of this time above grade, and therefore unable to widen their little valleys, although actively engaged in deepening them. On the other hand, even the largest rivers have not been able to maintain a graded channel in the rock ledges upon which they have been here and there superposed by the drift cover. They are still actively cutting down such ledges, but they are not yet able to widen the rock-notch that they are cutting; thus imitating the condition of their smallest branches, which have not yet been able to widen their little valleys even in clays and sands. Boulder clay or till is of a resistance between the feebleness of stratified drift and the strength of rock ledges. If a mass of till is discovered the stream may be successful in cutting down its channel to grade, and yet unsuccessful in opening a valley floor; and thus a boulder-clay "shut in" may be produced between open valley floors or "intervals" that have been eroded in weak stratified drift farther up and down stream. Little river, a mile southwest of Westfield, Mass., offers examples of this kind (page 333).

The small changes made in rock ledges during the development of an extended series of river terraces serves to indicate how short is the duration of the episode in which the alluvial filling of a valley is terraced, in comparison with the time needed for the erosion of the rock-bound valley itself, or still more with a whole cycle of erosion, in which a mountain mass is reduced to a plain of degradation.

While slow uplift is thus seen to be consistent with the production of many terraces, it is not consistent with their preservation, for it does not explain the diminution of the interscarp space from the higher to the lower levels. Indeed, the present rivers might tend to develop broader flood plains by strong lateral swinging at the faint grades now assumed than they had developed at the stronger grades during the earlier stages of possibly more active uplift and heavier load; and the broad low flood plains would necessitate the undercutting of all or nearly all the earlier high-level terraces by the present stream, and the concentration of nearly all the separate scarps in a single high-terrace front, as in Figure 2. Examples in which this condition has been actually attained are to be found in the valleys of various rivers, as will be more fully set forth on pages 328, 342, and 344. Single high-scarped terraces are indeed so common as to warrant the conclusion that high-level and intermediate terraces would nearly always be destroyed by the swinging of the river at a lower level, but for the occurrence of some special conditions by which they are preserved.

TERRACES CARVED BY STREAMS OF DIMINISHING LOAD. A graded river may be caused to degrade as well by diminishing its load as by increasing its slope, volume remaining constant. A diminution of load since the stage of glacial retreat is highly probable, for not only the streams that issued from the ice sheet but those also which washed the freshly-exposed drift-covered land surface were in all probability highly charged with detritus in late glacial and early postglacial time. Indeed, increase of load may have been almost as potent a cause of filling the valleys with washed drift as was the depressed attitude of the land in the north and the consequent enfeebled slope of the south-flowing rivers. As the ice disappeared and as the land surface was more or less covered with vegetation, the load of the streams should have been lessened, and they must thereupon have set to work to degrade the valleys that they had just before been aggrading, even if no change of slope had taken place. This process, if working alone, must have been very gradual, and might therefore have allowed plenty of time for lateral swinging and terrace carving. But, as before, no explanation is here found for the production of stepping terraces. On the contrary, when the diminution of load was further advanced the rivers would degrade their valley floors more and more slowly, and the tendency would then be to destroy all the earlier terraces by broadening the flood plain to a maximum.

That the rate of degradation by our rivers was really slow is proved by the flights of stepping terraces here and there in different valleys; and that the normal tendency of the larger rivers is to destroy nearly all the earlier-made terraces by opening broad flood plains at low levels is proved by the frequent occurrence of high scarps descending from the highest terrace plain nearly or quite to the lowest. Hence it is for the preservation of high-level and intermediate terraces rather than for their production that a more efficient cause than any yet discussed is to be sought.

PRESERVATION OF TERRACES BY ROCK LEDGES. What is more natural than that a river, swinging from side to side as it slowly degrades its valley floor, shall here and there be restrained on coming against a ledge projecting from the sloping valley wall; and that the deeper the valley is excavated the less breadth of free swinging can remain! This idea was first given explicit statement in Miller's paper on "River Terracing; its Methods and Their Results," as illustrated by observations in Scotland. After a review of earlier writings this author says:

"The modern rivers . . . have struck rock at very variable depths. In hundreds of cases, after winding freely about, encountering only soft clays and the like, and constructing terraces of various kinds, they have here and there become rock-bound, and prevented from pursuing their work of terrace-building after their former manner, as well as from destroying the terraces they had already made" (298). "When . . . the rivers commenced to work upon shallow, wide-bottomed valleys, soft and yielding in their nature, except where crossed by bars of rock . . . , they proceeded to plane far and wide, travelling from breadth to breadth to an extent never now equalled. With banks nowadays eight or ten times as high, and rock-bound at perhaps ten times as many points, it is no wonder that the modern rivers should seem to have 'run *in*'" (299, 300).

Rock ledges, however, are not here given the importance they deserve. The reader will not surely gain from Miller's article a full measure of the value of ledges in determining the pattern of terraces, and of stepping terraces in particular. Hence a more detailed statement of the relation of ledges to terrace pattern and to terrace development seems desirable, especially with reference to the valleys of New England, where this explanation of terraces has not previously been applied.

It should be further noted that certain postulates of Miller's essay do not command entire assent. He states that "it is not allowable to have recourse to coast elevation, or climatic changes, or periodicity of any kind, without first proving that the terraces range in opposite pairs" (304, 305). This seems to be an unnecessary limitation of possibilities; for, as is here explained on page 305, a river that is impelled to gradual degradation by a slow rising or tilting of the land may produce unpaired terraces as it wanders to and fro across its valley floor. On another page Miller concludes that rivers "cannot but concentrate their channels as they excavate them, unless the amount of planation is out of all proportion to the rate of deepening" (300), and seems to imply in this statement that a large ratio of lateral erosion to degradation, such as is here assumed for our New England rivers, and further considered in later sections, is an improbable ratio. To this it may be answered that the occurrence of stepping terraces at one and another point in our larger valleys certainly justifies the assumed ratio by showing that lateral swinging should be measured in hundreds or thousands of feet at many successive stages of degradation, while the total degradation is usually to be measured in tens of feet and seldom exceeds one or two hundred feet. A possible reason for the difference of values given to this ratio may be that Miller's studies were directed to the moderate-sized rivers of Scotland, while the best terraced valleys in New England are those of large rivers like the Connecticut and the Merrimac and their stronger branches; and, as has been already pointed out, a large river may swing actively during an uplift that gives a small river no time for anything but down-cutting. These two items are, however, of secondary importance in Miller's theory compared to rock ledges.

In reviewing various other essays of earlier dates several suggestive passages have been found, hinting at the importance of rock ledges. Adams makes the following statement: "If a terrace has been formed before the complete removal of the obstructions in the channel [the context shows that these obstructions are 'solid rock'], the same process must have been repeated within the new and narrower level of interval. We should thus have a second terrace. Repetitions of the process in cases where the obstructions were not entirely removed would occasion a greater number of terraces" (146). Something more explicit is found in Edward Hitchcock's "Surface Geology." In describing a middle section of the Connecticut valley, where the terraces became famous from the writings of this author, it is said that "the rock often projects through the terraces" (18), but the service of the rock in protecting the overlying terrace from being cut back is not announced. Farther on a description is given of the basin of the Westfield river, where the effect of ledges in determining the number and pattern of the terraces is very striking (see page 331); here it is briefly stated that "the materials of which all these terraces are formed are clay, sand, and gravel, though the red sandstone shows itself occasionally near the river" (20). The secret is told in an account of the terraces of the Deerfield: "The river would encroach still further upon this hill, had it not struck a ledge of red sandstone, which will at least retard its lateral erosion" (19); and again, "the reason why those [terraces] on Pine hill remain, I find to be that they rest on a protuberant mass of red sandstone. On the west side of the hill . . . is an ancient bed of Deerfield river . . . which was prevented from making any further lateral encroachments by the underlying rock" (20). Yet in spite of the understanding thus shown of the importance of ledges in these particular instances, the generality of the relation of ledges and terraces is not brought forward; and the above instances of the local restraint exercised by ledges have never been quoted, so far as I can find, by any of the many readers of Hitchcock's well-known essay.

A fuller recognition of the part played by defending ledges is to be found in Emerson's "Geology of Old Hampshire County, Massachusetts." It is here said that the Connecticut river in the neighborhood of Holyoke "has now cut its bed deep in the sandstones and is thus prevented from oscillating" (730). A little farther down the valley "the river early became entangled in rock and has cut only vertically" (733). In the northern part of the state "the river everywhere cut down rapidly to rock and has not swung widely to east and west, but has been condemned from the beginning to rock-cutting" (733). "Across Chicopee there is a fine, low terrace bounded on the east by a high scarp of the high terrace, which everywhere shows till in great force beneath the sands of the old lake" (730; see also 627, 632). It should be noted, however, that these passages are chiefly concerned with the occurrence of trenches, floored with rock and lined on both banks with ledges. The part played by an isolated ledge of rock or by a bank of till in preventing the further swinging of the river and thus defending the terraces above it is not brought forward.

ORIGIN OF TERRACES IN NEW ENGLAND. Three conclusions may now be stated in order that the reader may have in mind the end to which the preceding and following pages lead. First, a diminution of stream volume may have taken place during the terracing of our New England valleys, but it has not been essential to the production of the observed terraces. Second, the terracing rivers have slowly degraded their aggraded valleys while actively swinging from side to side; degradation probably being the result of the combined action of a slow northern uplift and a gradual decrease of load, and in spite of a probable decrease of volume. Third, the chance discovery of rock ledges by the swinging river is the chief cause of the systematic diminution of interscarp space and of the preservation of terraces, as seen in a typical section of stepping terraces.

A full statement of the process of terracing therefore involves a consideration, first, of the behavior of a free-swinging, slowly degrading river; and, second, of the constraint that may be imposed on such a river by the accidental encounter with previously buried ledges at various points in its course and at various stages in its history. This anticipatory statement may aid in the understanding of the following pages.

III. The Theory of River Terraces.

Plan of Statement. The previous paragraphs have given a general consideration of several theories of river terraces, with the result of deciding that one of them offers a much better explanation of observed facts than the others. It is now proposed to examine the successful theory with more care, first, by making a somewhat detailed study of such processes of river action as are involved in the theory; second, by deducing with some minuteness the various patterns of terraces that can be formed by these river processes. It will then be possible to make in Part IV. a thorough test of the verity of the theory by confronting its deduced consequences with the facts determined by observation.

It should be understood that the deductive character of the succeeding paragraphs is more apparent than real. Many features of river work here presented as deductions were discovered by observation. It is true that an expectation of certain occurrences had been aroused by the deductive consideration of certain processes, but there has been so continual an interweaving of observation and theory during the growth of these pages that it is now rather difficult to determine the order in which the various items here recorded came to mind. It is therefore chiefly for the sake of a continuous presentation of the theory of river terraces that a largely deductive treatment is here adopted. When the whole theory has been apprehended, it is relatively easy to test its verity by observations pertinent to its different parts.

The other theories of terracing, regarded as unsuccessful in the preliminary inquiry of Part II., should be more thoroughly considered before they are discarded ; but, inasmuch as the further they are examined the less competent they seem to explain the facts observable in the terraced valleys of New England, it does not seem worth while to give them any more explicit consideration here.

Behavior of a Wandering River. The diagrams introduced in the following sections represent several successive stages in the process of slow degradation by a wandering river. The postulates as to river behavior on which the diagrams are based are: (1) The degrading stream continually maintains an essentially graded condition. (2) The lateral swinging of the meandering channel is very much faster (a hundred-fold, for example) than the degradation of the valley floor. (3) The breadth over which a free river (not constrained by ledges) tends to swing laterally is greater than the breadth of the meander belt (the belt included by tangents to the meandering channel). (4) An individual meander tends to enlarge its radius and to work its way down the valley until it may be abandoned at season of high water for a short cut across a flood-plain lobe, or at any season (but usually at high water) for a cut-off through the narrowing neck of a lobe. It is believed that abundant justification may be found for all these postulates, either in the observed behavior of a graded river, or in the success with which they lead to an understanding of the peculiar patterns of our terraces. The several postulates may now be reviewed.

(1) If the change in the ratio of load to carrying power (volume and slope) proceed very slowly, a river may remain in an essentially graded condition all through the process of aggrading or of degrading its valley, and through the change from aggrading to degrading. It is true that the graded condition depends on a balance between load and carrying power, and it would at first sight appear that any change in either quantity would destroy the balance and throw the river out of grade. But if the change is only by a quantity of the second order — that is, if either load, volume, or slope is changed only by a differential of its value in a unit of time — adjustment to the new condition will follow so immediately that no failure of adjustment will be noticeable. A similar maintenance of an essentially graded condition obtains in the degradation of graded (waste-covered) hillsides as they pass from maturity to old age. It is, however, not likely that the very slow degradation of a valley floor which accompanies the advance from maturity to old age in a normal cycle of rock erosion will result in terraces, because

the general processes of weathering may lower the flood plain about as fast as the river sinks to a fainter and fainter slope. The rate of degradation of a terracing river in a drift-filled valley, resulting from a climatic change or from a land movement, may therefore be allowed a decidedly higher value than that of an ageing river in a normal, undisturbed cycle.

(2) It is well understood that a graded stream may work actively in wearing or building its banks laterally, however slowly it aggrades or degrades its valley floor.

(3) There are abundant examples of rivers whose lateral oscillation or swinging carries them from side to side of a flood plain that is much wider than their meander belt. The Mississippi is a noted case of this kind. Its meander belt is six or eight miles wide in a flood plain whose enclosing bluffs are from twenty to sixty miles apart. A similar relation may be seen in many meadow flood plains, drained by small brooks.

(4) The fourth postulate involves a principle of river action which may be familiar to hydrographers, but which is nevertheless not commonly stated. Imagine a stream in a broad flood plain passing from a straight stretch or tangent to a well-defined curve. On the tangent A B, Figure 7, the thread of fastest current might, as far as local control is concerned, lie along the middle of the channel, or indifferently on one side or other of the middle line. On entering the curve the fastest current is gradually shifted, B C, towards the outer bank of the channel, and there flowing steadily all around the curve C D it determines the line of greatest depth. On passing from the curve the thread of fastest current is necessarily delivered to the next down-stream tangent, D E, on the down-valley side of the channel, and only after flowing for a significant distance will the fastest current gain a path near mid-channel. If the curves or meanders are close set, so that one curve passes directly into the next one with no intervening tangent, then the thread of fastest current must, on passing the point of inflexion, enter the upstream end of the next curve near its inner or convex bank, and only gradually be displaced towards the outer bank as inertia has time to bring about its usual effect.

As a result of this systematic displacement of the fastest current from the mid-channel line the bank that it approaches will be worn away, while deposition will take place along the bank from which the fast current is withdrawn. The stream will therefore tend to wear away the bank on the outer side of its curves (but perhaps failing to begin this action just at the beginning of the curves), and on the down-valley side of short tangents. The curves will thus increase in radius and arc and the meander belt will widen, while each meander will tend to move slowly down the valley. The flood plain must be scoured out for a certain stretch, N N^1, around the concave banks and along the up-valley side of every lobe; while a scroll of new flood plain, M M, is added around the end and on the down-valley side of the lobe.

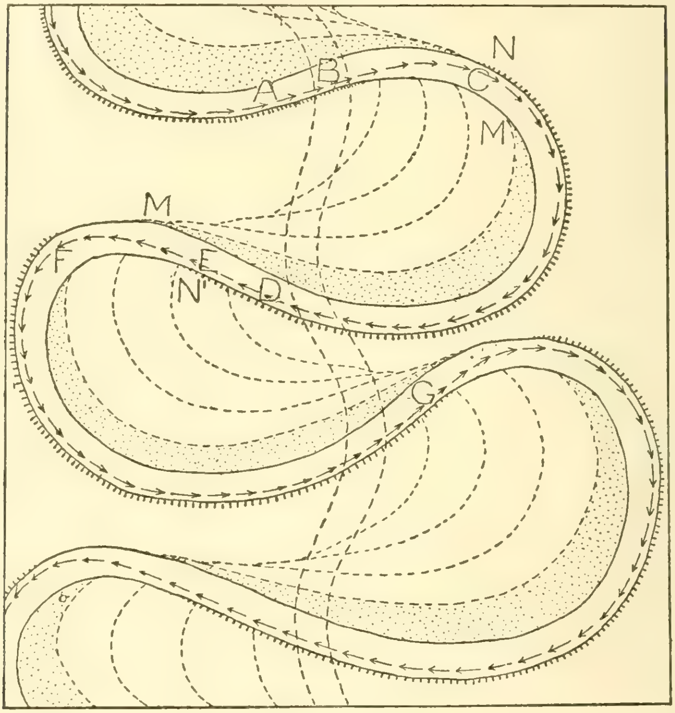


Fig. 7.

All this may be easily recognized in the meanders of a meadow brook; and that it occurs even in the Mississippi is abundantly illustrated in the large-scale maps (three inches to a mile) published by the Mississippi River Commission (see specially Charts 36, 38, 39), where the lines of flood-plain growth pass around the end and along the down-valley side of each lobe, while they are cut across by the encroaching river on the up-valley side of the lobe, as indicated in Figure 7. Still more definite proof of this feature in the behavior of a meandering river is found in the new edition (1900) of the Preliminary Map of the Mississippi (one inch to a mile), in which a red overprint indicates the new position of the channel, as determined some fifteen years after the previous survey (see especially sheets 14, 16, and 18).

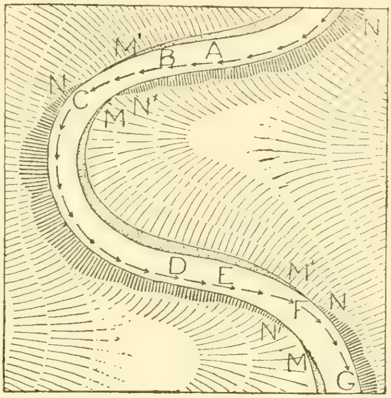


Fig. 8.

The same down-valley shifting of the meanders is seen in the enclosed meanders of many rivers, typified in North branch of the Susquehanna, Figure 8. This fine river has incised its course beneath the uplands of northern Pennsylvania. The upland spurs that enter the river curves have been subjected on their up-valley sides to a persistent sweeping that is but little less effective than that by which the curved re-entrants between the spurs have been scoured out. The up-valley side of the spurs have strong bluffs, as different from their gentle down-valley slopes as are the high lateral bluffs that enclose the curves from the gentle terminal slopes of the spurs. It is noteworthy that in this case of a rock-walled valley, the down-valley shifting of the curves does not seem to have been more than fifteen or twenty times greater than the degrading of the river channel in the latest period of valley trenching; while in the case of terracing streams in drift-filled valleys, the first of these changes exceeds the second in a much higher degree. It may be further noted that the North branch of the Susquehanna above Wilkes Barre seems for some time past to have ceased deepening its valley, for narrow double-curved scrolls of flood plain are now systematically added to the outer end and the down-valley side of the spurs, as may be especially well seen just above Tunkhannock, and as is indicated by the dotted areas M M′, opposite the under-cut bluffs, N N′, Figure 8.

Other examples of meandering valleys, exhibiting the systematic lateral growth and down-valley shifting of the meander curves, might be instanced; a few of them are mentioned in my paper on the Drainage of Cuestas (89). It is my hope to give at another time a fuller account of this phase of river development, and then to show how satisfactorily the stage of development may be stated in terms of the flood-plain pattern.

The four postulates above announced concerning river action may therefore be taken as well supported.

A natural limit is set to the dimensions of a growing meander curve on a flood plain by the formation of short-cuts across flood-plain lobes at time of high water, or of cut-offs when the narrowing neck of a lobe is finally worn through, a roundabout course being in both cases abandoned for a more direct one. It may therefore be expected that the abandoned channels, such as are preserved in ox-bow lakes on existing flood plains, and in swampy half-filled channels at the back border of many terraces, will on the average show a larger radius of curvature than the curves of the existing river; and the maps of the Mississippi give some support to this expectation. Emerson has pointed out (735) the tendency of our New England rivers and streams to form loops or ox-bows on the right of their general course, from which they return to a nearly direct course by short-cuts or cuts-offs, only to begin again the work of right-handed loop-cutting. He states that the Connecticut near Northampton, Mass., has seven deserted loops on the right (west) and none on the left; some of its tributaries have sharp bends and ox-bows thirty times as numerous on the right as on the left of their course. It is naturally suggested that this asymmetry is the result of the deflective force arising from the earth's rotation.

Terminology of Wandering Rivers. The terms already introduced regarding rivers that wander about their flood plains may now be summarized and somewhat extended. The space enclosed between tangents drawn outside of the curves or meanders of the stream is the meander belt. This belt will widen while the meanders are normally wearing their outer bank; but on the occurrence of a short-cut across a flood-plain lobe or of a cut-off through the narrowing neck of a lobe, the belt will locally collapse. Here the river course becomes relatively direct for a time, only to develop serpentines again as new meanders are established. The progressive movement of the meanders down the valley will be called sweeping. Up-stream and down-stream will be used in their ordinary sense, but up-valley and down-valley will be substituted when it is desired to indicate a more general direction than that of the circuitous channel.

The lateral movement of the meander belt from one side of the valley floor to the other will be referred to as swinging. It is not always possible to distinguish between the true lateral swinging of the meander belt as a whole and the more local shifting of an irregularly sweeping meander. The compound movement of sweeping meanders in a swinging meander belt will be called wandering, this term being fully justified when it is noted that many unsystematic irregularities must be developed in a stream channel, whereby it will depart significantly from the simple and regular movements here considered. The whole breadth of the valley floor that may be worn down by the stream will be called the belt of wandering; this corresponds to many of our flood plains or "intervals."

In an ideal case, a regularly growing pattern of meander curves might be imagined slowly sweeping down a valley, the meander belt collapsing here and there, now and then, but growing again to its ordinary breadth as new curves are developed in the place of the old ones. At any point in the valley, an endless procession of meanders would sweep past.

If it be now supposed that the wandering stream is slowly degrading its valley floor, each meander will sweep past a given point at a slightly lower level than that of its predecessor; and each time the meander belt swings across the valley from one side to the other and back again, it will return at a distinctly lower level than that at which it left. The flood plains formed at different stages of this leisurely process will differ in altitude, and all of them will be inclined gently down the valley. It is the remnants of these flood plains that form our terrace plains.

IDEAL TERRACE PATTERNS: EARLY STAGE. Soon after the stage of degradation has been definitely established and the meandering stream begins to swing across the valley at a little lower level than before, a condition represented in Figure 9 may be reached. In this figure, as in a number that follow, it is supposed that the view is taken from a considerable height, looking northwest across the valley of a south-flowing river. The terrace plains are left blank in most of the diagrams. The western meander in the foreground of Figure 9 is now scouring out a curve in a low concave terrace scarp, B, the ninth of its kind within the limits of the diagram. A small portion of a terrace, A, of slightly less height, is shown in the immediate foreground; it may represent the work of the preceding westward meander, while the next following westward meander is cutting out a deeper terrace, C, in the background. Terrace A may be taken as one of the first marks made by the degrading stream. Terrace B is of greater height than A, because A has been under-cut and consumed in the production of B, except in the immediate foreground. Terrace C is as yet independent of B, and therefore shows a height to be measured only by the few inches or feet of depth to which one sweeping meander cuts below the plain of its predecessor. The curves and cusps of Terrace B result from a vacillation of the meander during its down-valley progress; a rather sharp cusp being left between B 2 and B 3, while the curves from B 3 to B 9 have arcs so small as to join in a nearly straight terrace front.

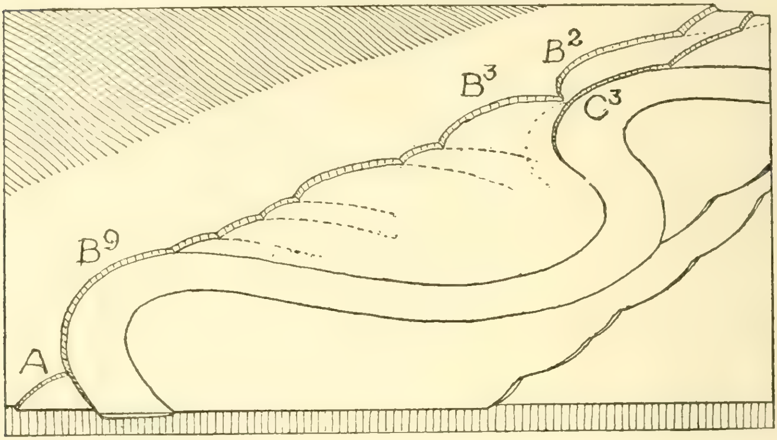


Fig. 9.

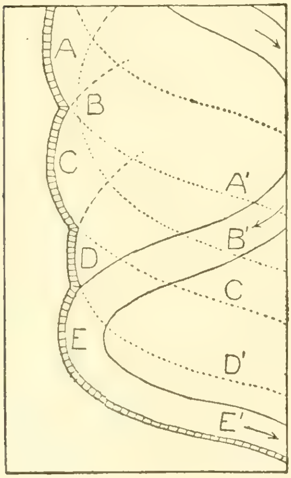


Fig. 10.

It may be noted that the small curves by which a nearly straight terrace front is usually formed are as a rule to be expected only towards the side of a valley, and less commonly on a terrace spur that advances into the valley. For example, in Figure 10 the little curves A, C, D, E, record so many positions of the meander apex, and will not now be destroyed until a later meander under-cuts them. Scarps of this kind may be called one-sweep scarps; and their cusps, one-sweep cusps. Several similar cusps are shown in Figure 9. The longer curve, E E′, cut by the advancing front of the meandering river, may be abandoned if the river is diverted by a short-cut to a new course, and if so the advancing terrace spur will be smooth trimmed.

A terrace whose scarp has been almost evenly trimmed by the small vacillations of a down-sweeping meander will face the axis of the valley. A terrace whose scarp has been under-cut by the forward half of a down-sweeping meander will face obliquely up the valley, as in the foreground of Figure 10. Inasmuch as the normal progress of meander-sweeping is down the valley, it would seem, at first thought, that no terrace scarps could be carved so as to face in that direction; but on second thought it will be seen that the lateral growth of a meander may cause part of the curve to grow up-valley faster than the meander is carried in the other direction by the normal down-valley sweeping of the meander system; and in this case a terrace scarp facing obliquely down-valley will be carved. An example of this kind is shown near the foreground of Figure 11. It is manifest that the development of terraces facing down-valley will be favored wherever the down-valley sweeping of a group of meanders is for any reason checked while the enlargement of their curves is continued.

There can be little doubt that the height of terraces produced by the action of successive meanders would be very small, hardly measuring as many inches or quarter inches as actual terraces measure in feet. Let it therefore be now supposed that after a series of one-sweep scarps has been carved, the river swings away from the western side of its valley and for a time occupies itself in carving scarps on the eastern side. Many meanders will have swept down the valley during the eastward swing of the meander belt, each meander leaving its faint scar on the valley floor. When the river swings westward again, it will be working at a lower level than before, and as it then once more undercuts the high plain, a distinct terrace with a scarp of ten or twenty feet will be formed. Terraces of distinctly different levels may therefore usually be taken to represent different swings of the meander belt; terraces that represent only the sweeps of successive meanders while the belt remains almost stationary must be so faint as to be hardly noticeable.

A cusp which results from the slightly vacillating forward sweep of a single meander, as B 6, B 7, etc., Figure 9, has already been called a one-sweep cusp. The terrace plain extending forward from the base of such a cusp will be a smoothly continuous surface on both sides of the apex. When the two parts of a terrace plain on either side of a cusp differ in height by a foot or two, they are probably the product of different (but not necessarily successive) meanders; and such a cusp may be called a two-sweep cusp, because the two levels probably represent different sweeps in the meander belt. When the difference in height is a number of feet, the cusp is probably a two-swing cusp, because the two levels are then best explained by different (but not necessarily successive) swings of the meander belt. Examples of these forms are often met with.

IDEAL TERRACE PATTERN : MIDDLE STAGE. If the sweeping and swinging of the river continue until, as in Figure 11, a fifth return of the meander belt to the western side of the valley is accomplished, a terrace pattern of some complication may result. Few and small remnants of the higher terrace plains are to be expected at this stage, for they have been repeatedly undercut and destroyed. Larger and more numerous remnants of the lower plains may be still preserved, for they have been less frequently attacked. A triangular portion of the third-swing plain is shown in the middle of the figure ; on the right appears a still larger piece of the fourth-swing plain, from which the river was withdrawn by a short cut across the flood plain (not shown in the figure), leaving an unfilled channel which now guides a small brook. The fifth westward swing of the river has, during the down-valley sweep of a single meander over the length of the diagram, undercut and destroyed part of the fourth-swing plain on the right ; it has destroyed all of the fourth-swing and part of the third-swing plain in the middle and all of the earlier plains toward the left, where the meander undercuts the high scarp and recent landslips have occurred. The greater the number of swings, the smaller and rarer will be the remnants of the higher terrace plains, unless some special control is present to preserve them.

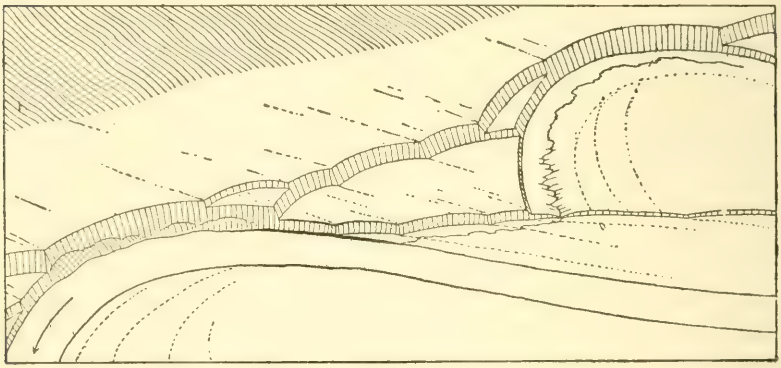


FIG. 11.

A special interest attaches to the form and arrangement of the cusps that are produced by the chance intersection of the curved terrace fronts. In the two-sweep or two-swing cusps, two patterns may be produced, according as the higher scarp is on the up-valley or down-valley side of the cusp, as in Figures 12 and 13. The higher scarp is evidently the younger of the two that unite in the cusp; it is continued in direction, but with less height beyond the point of intersection. From the appearance of a letter Y in the shaded scarps of the diagrams forms of this kind may be called two-swing (or two-sweep) cusps with an up-stream or a down-stream Y-stem, as the case may be. All the elements of such cusps are variable. The location of the cusp is at the chance intersection of two lines that have no particular relation to each other. The angle of the Y may vary through a large range. The heights of the scarps have no definite relation, except that the higher single scarp must be the sum of the other two.

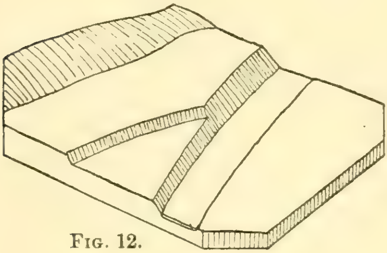


FIG. 12.

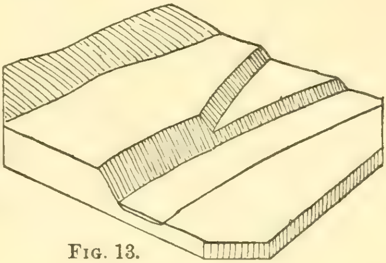


FIG. 13.

A series of one-sweep cusps may occur with some regularity along a valley side; but two-sweep and two-swing cusps cannot be expected to show so definite an arrangement, unless under the control of something more systematic than the action of the wandering stream. In Figure 11, for example, two series of one-sweep cusps in the middle of the diagram stand in normal down-the-valley order; but all the two-swing cusps are located indifferently to one another. So on the left side of Figure 6; but on the right side of that figure, three one-sweep cusps on successive terraces are placed in line, one forward of the other, as if in some way systematically related or subject to some common control.

In view of these various ideal combinations, it is evidently desirable to analyze the special configurations that may be due to river action alone, in order to detect more surely the patterns that must be referred to some other cause.

A later-made one-sweep cusp may occasionally chance to stand in front of an earlier-made one-sweep cusp, as in the further part of Figure 14; but it is evidently out of the question that four cusps should gain a systematic position of this kind, as in the center of Figure 15, without some common control. Whenever such an arrangement is found, special examination should be made of it. Again, while a two-swing cusp is of common occurrence, a three-swing cusp, Figure 16, must be rare, for it involves the intersection of three unrelated lines in a systematic manner; and a four-swing cusp, Figure 17, is practically an impossible occurrence. True, a three-swing cusp must be produced at a certain stage of the change shown in Figure 18, where a sweeping meander is undercutting its scarp and thus pushing one two-swing cusp, A, towards another two-swing cusp, B; for at a certain stage in the

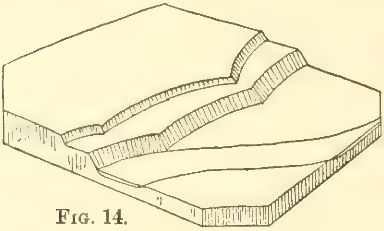


Fig. 14.

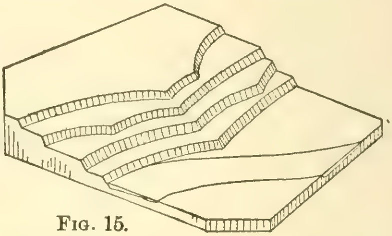


Fig. 15.

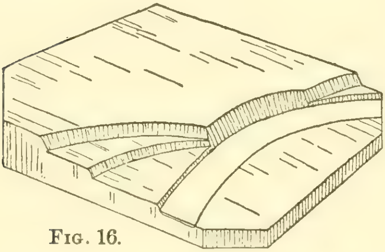


Fig. 16.

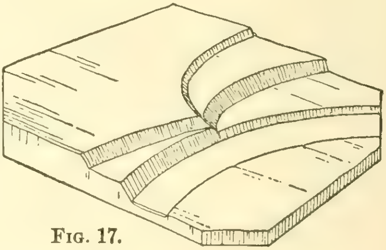


Fig. 17.

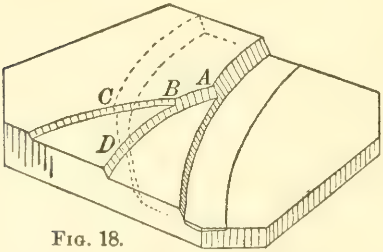


Fig. 18.

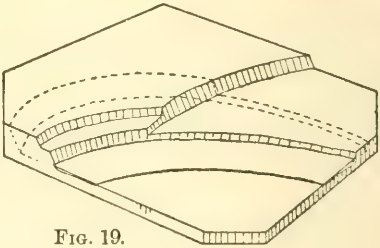


Fig. 19.

undercutting, A will be pushed into coincidence with B, thus forming a three-swing cusp. But it is very improbable that this temporary stage will be preserved. The undercutting will continue and the temporary three-swing cusp will then be divided into two two-swing cusps, C and D. The three-swing cusp can be preserved only when, just at the moment of its formation, the stream is withdrawn by a short-cut or a cut-off, and such a coincidence must be of very rare occurrence. Withdrawals of the stream may, however, happen likely enough before or after the momentary stage of the three-swing cusp; and the various patterns thus producible are indicated by the full and broken lines in Figures 18 to 21. The eight possible cases of this kind result from different combinations of the up-valley or down-valley half of a meander with two-swing cusps of up-stream or down-stream Y-stems. Evidently, then, no combination of unguided sweeping and swinging meanders will produce an orderly grouping of cusps such as is shown in Figure 15.

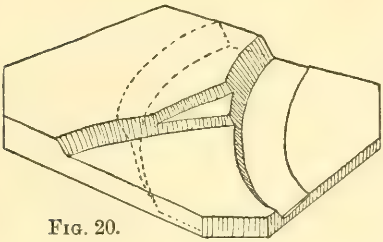


FIG. 20.

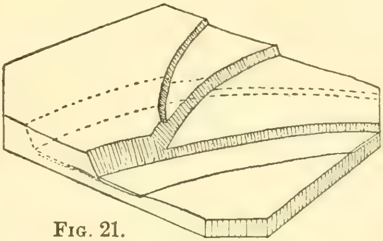


FIG. 21.

IDEAL TERRACE PATTERNS: LATE STAGE. When the causes that determine the degradation of a valley floor weaken and disappear, the stream will repeatedly swing to and fro on about the same plane. Even the basal terraces of a series may then be almost completely swept away by the wandering river, as in Figure 22, and the whole descent from the high-level terrace to the existing floodplain may be, for considerable distances along the valley side, united in a single strong escarpment. The conditions under which this result may be brought about are: first, the attainment of nearly fixed values of volume and load, such as might be reached when a glacial climate had given way to a milder climate and the latter had become well established; second, the cessation of any slow uplift by which degradation had been initiated or aided; third, superposition of the stream on a strong rock sill on which corrasion is very slow. Under these conditions, a stream would almost cease to degrade its channel, and would then devote practically all its energy to lateral cutting. The stream would wander back and forth across its valley floor, unimpeded save by its flood-plain bank, until it came against a lateral terrace; and the terrace would be worn back to the limit of the belt of wandering. Sooner or later the stream would consume all the high-level and intermediate terraces, pushing back their united scarps into a single scarp by which the highest terrace plain would then descend at once to the flood plain. Stepping terraces would no longer characterize this stage of valley development; but a few low terraces might remain not yet consumed here and there, as in Figure 2.

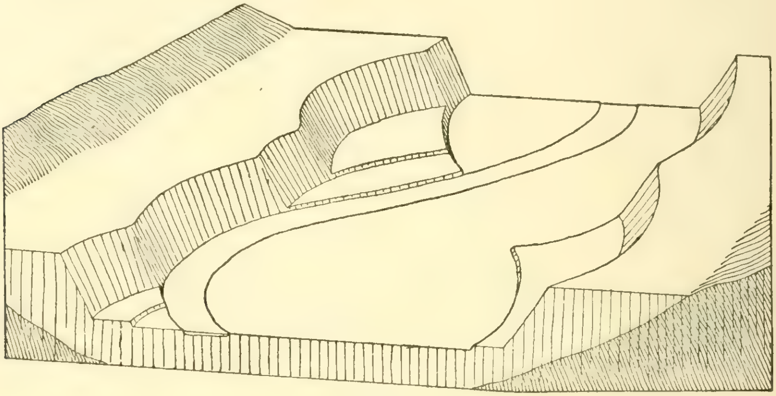


FIG. 22.

Miller seems to suggest that an increase in the height of terrace scarps is in itself a cause for a decrease in interscarp space. "The restraint exercised by rock upon the modern rivers strengthens their natural tendency, of which sufficient account has not been made, to occupy narrower portions of valleys the more they deepen them. It has been too hastily concluded, because rivers now occupy narrowed valleys flanked by terraces comparatively broad, that therefore they have vastly shrunk, — from dimensions, in fact, proportional to the greater breadth" (299). He then goes on with the statement already quoted regarding the "banks nowadays eight or ten times as high" as formerly. It thus seems to be implied that it is "natural" for the interscarp space of a stream of constant volume to lose width; and that not only rock ledges restrain the breadth of the belt of wandering, but that the increase in height of the enclosing scarps also has a share in determining this feature of valley form. A similar opinion is expressed by Gilbert (133). This seems to me an unnecessary conclusion, unless rapid elevation up to a recent date be postulated also, as is perhaps implied by Miller in a later sentence. Certainly, so far as increase of scarp height in New England valleys is concerned, it has not sufficed to prevent the broadening of the valley floor and the consumption of terraces at higher levels, so long as the terraces consist only of clay, sand, and gravel.

It may be noted that if there had been a diminution of volume during the deepening of a drift-filled valley, the obliteration of stepping terraces would be delayed, but not prevented. It has already been explained that some diminution in stream volume is certainly probable. It may now be added that many valleys have, in spite of this very probable decrease of stream volume, already reached in one or another part of their length the late stage of terracing just described, in which all the descent from the highest terrace to the flood plain is concentrated in a single scarp, and that in many other parts of these valleys only a few basal terraces remain beneath the strong scarp of the high terrace. It thus becomes all the more probable that diminution of volume is not an important cause of the decrease in the breadth of the interscarp space, and that where stepping terraces occur, they must be in large part referred to some special and local cause. Such a cause is found in the presence of rock ledges, as suggested by Miller; and to that element of the problem we may now turn.

DEFENDED TERRACE CUSPS: EARLY STAGE. It has thus far been tacitly postulated that no buried ledges should be discovered by the wandering river. Such, indeed, is the condition usually assumed in the cross-section of a series of typical terraces, as in Figure 1. Let a new series of terraces now be developed, in which ledges shall here and there be discovered as the river degrades its valley floor to greater and greater depths. It is evident that the number of such ledges may vary greatly. They might be numerous and frequently encountered by a terracing river in a narrow valley with rugged rock walls and bottom; they might be almost absent and hardly ever discovered in a broad valley that had been heavily aggraded. In all cases it is important to note that the slope of a ledge face will seldom be as steep as the average slope of a terrace front, which may be as much as 30° in freshly cut scarps.

As before, the river wanders about freely so long as it is working on unconsolidated sands and clays; and thus several low terraces may be formed in the manner already described. But when a ledge is encountered in the river bank, as at the left forward edge of Figure 23, the rock is practically indestructible. The stream will in a comparatively short time swing away, after having altered its course more or less in a fruitless effort to wear back the obstacle. The ledge thus comes to determine a cusp in the terrace front. A salient of this kind may be called a defended cusp, in distinction from the accidental or free cusps described in the previous sections; the terrace behind it cannot be destroyed by the stream.

Following the colloquial style often adopted for field descriptions, a terrace of this kind is sometimes entered in my notes as a "can't-be," in contrast to the low "not-yet" terraces of Figure 22.

It should be noted that the ledge here considered does not determine the depth to which the river may work; the rock is exposed only in the river bank and enters but a little distance into the channel. The slope of the river and the depth to which it has cut at this or any other point in its course are assumed to be determined in all cases thus far detailed by the maintenance of an essentially graded channel with respect to some controlling baselevel further down stream; the sea at the river mouth, a larger river into which the smaller stream enters, or a broad sill of rock that stretches all across the channel, somewhere further down the valley.

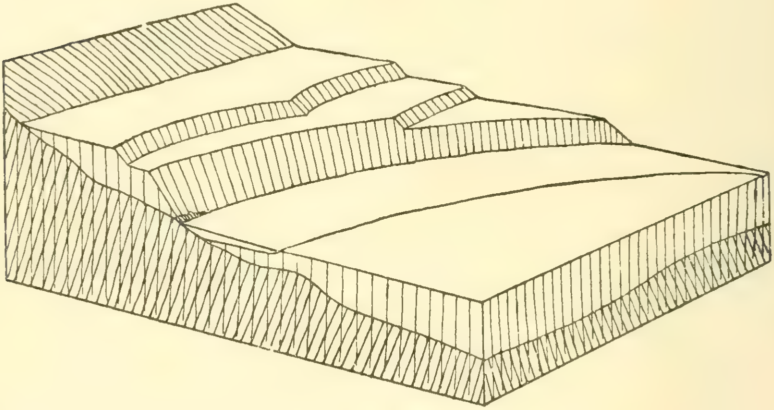


Fig. 23.

When the withdrawing stream swings back again at a lower level, as in Figure 24, it cannot often under-cut and destroy all of the terrace on whose back border the first ledge rises, because, as has been noted, the slope of the ledge is seldom so steep as that of the terrace scarp. A second encounter with the ledge will usually be made before the swinging stream has entirely consumed the terrace of the previous swing. Every return of the swinging river against a sloping reef of rocks will thus be recorded by a little strip of terrace behind the defending ledges, and a flight of stepping terraces will necessarily be produced wherever a large group of ledges slopes under the valley drift into the belt of river action. The length of the ledge exposed at the back of each terrace may be but a few feet, but its effect will be prolonged by a trailing terrace, as it may be called, stretching hundreds or thousands of feet along the valley side. It is in this way that the best flights of stepping terraces are produced.

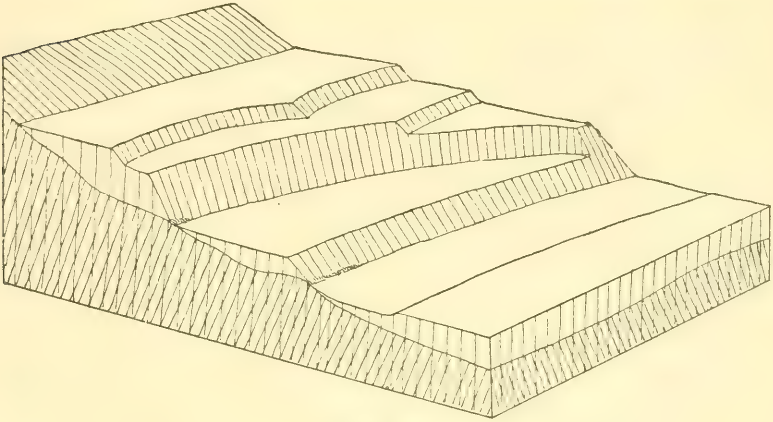


FIG. 24.

The special features of terraces associated with defending ledges are next to be examined.

SLIPPING MEANDERS AND BLUNT CUSPS. It has not yet been possible to discover by observation how a down-sweeping meander will make its passage past a ledge; but it may be inferred from the forms of terraces found in various valleys that a stream has two methods of procedure in such an exigency. The first is considered in this section, and is illustrated in Figures 25 to 28; the second is taken up in the next section, with Figures 29 to 31.

Let it be supposed that the river in Figure 25 is now making its fourth swing against the western side of its valley, and that a buried ledge lies a few hundred feet back of the group of free cusps in the middle of the diagram. The ledge is discovered in Figure 26; it lies somewhat below the apex of a down-sweeping meander. Assuming that the meander curve is to remain practically unchanged, it can pass the ledge only by withdrawing somewhat towards the axis of the valley; it may thus, as it were, slip by the obstacle that stands immovable in its way. The stream is represented as having just slipped past the ledge in Figure 27, and as having swept somewhat farther down the valley in Figure 28.

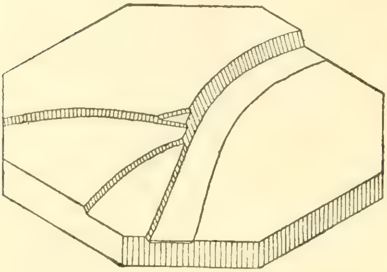


Fig. 25.

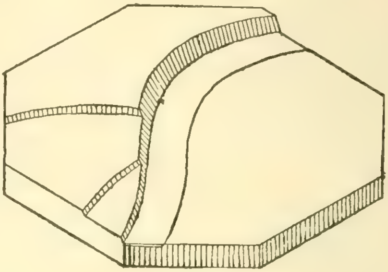


Fig. 26.

All records of the first and third swing of the river are now destroyed, so far as this part of the valley is concerned; the terrace front shows a high, defended, one-sweep cusp, a free two-sweep cusp with an up-stream Y-stem, and a free one-sweep cusp.

The ledge at the base of the defended cusp may come to be more or less concealed by the sands that are washed down from the weathering scarp. In time it may be entirely covered, and its presence will then be known only if a road cut or a boring reveals it. It is therefore quite possible that some apparently free cusps are really defended cusps, with their defending ledge ambushed beneath a thin cover of soil.

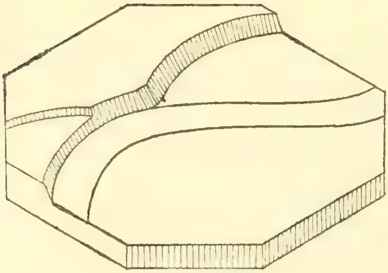


Fig. 27.

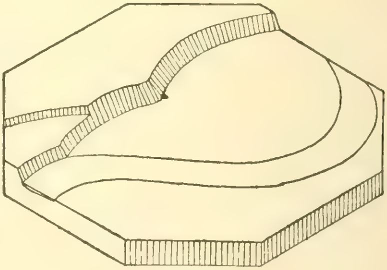


Fig. 28.

Compressed Meanders and Sharp Cusps. Let it now be supposed that the river in Figure 26 is unable to slip past the ledge. The front of the curve is held fast; the apex of the curve bends outward and cuts a curved re-entrant in the terrace front next up-stream from the ledge, as in Figure 29. The meanders further up-stream continue their advance and the meander next to the ledge is therefore compressed to a relatively strong curvature, as in Figure 30. The defended cusp is now sharpened. It may come to point somewhat up the valley. The compressed meander cannot slip by the ledge; there is no escape for the stream save by a short-cut across the narrowing flood-plain lobe at time of high water; thus the condition of Figure 31 will in due time be developed. A rather sharp cusp, one of whose sides faces up the valley, will be produced, and the great concave scarp adjacent to it will have an abandoned channel at its base.

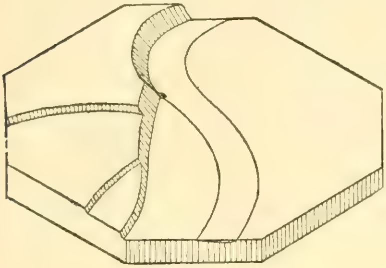


FIG. 29.

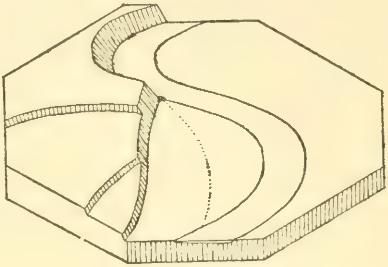


FIG. 30.

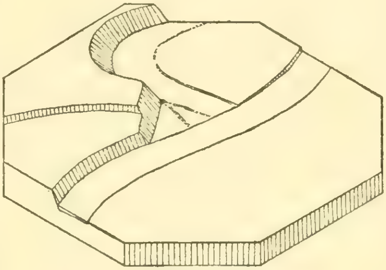


FIG. 31.

TERRACE FRONTS NEAR DEFENDED CUSPS. The difference between the behavior of slipping and of compressed meanders may be inferred to depend on the position of the obstructing ledge with regard to the apex of the meander. If the ledge is discovered near the apex of the meander, the stream may slip past the obstacle, as in the example first given. If the ledge is encountered near the point of river inflexion — that is, on the tangent between two meanders, — compression of the meander up-stream from the obstacle is likely to result.

In both these cases the defended cusp is likely to be associated with several short curves and free blunt cusps for a little distance down-valley; while a rather long re-entrant curve usually joins its up-valley side. The short curves and blunt cusps may be blended so as to produce a convex terrace front for a little distance down-valley from the ledge; and this convex front will be separated from the long concave re-entrant by a more or less pronounced angle at the defended cusp. The reason of this may be easily understood from Figure 32. The ledge was here first discovered by a down-sweeping meander, of whose first work only the short scarp A remains. The meander was then compressed so as to scour out a large concave re-entrant, and was withdrawn from the channel, B, at its base by a short-cut (outside of the diagram). A meander on the new course of the stream, swinging westward, trimmed off the terrace front in successive lines, C, D, E; but as this meander had no definite relation to the ledge, and as the general sweeping of its curve was down-valley, it did not trim the terrace front with any special regard to the down-valley side of the defending ledge. In brief, the tendency of a stream to sweep its meanders down-valley commonly results in trimming off the terrace front close to the up-valley side of a defending ledge, but it is only by chance that the terrace is worn away close on the down-valley side of the ledge. The pattern here deduced may be matched in many actual examples.

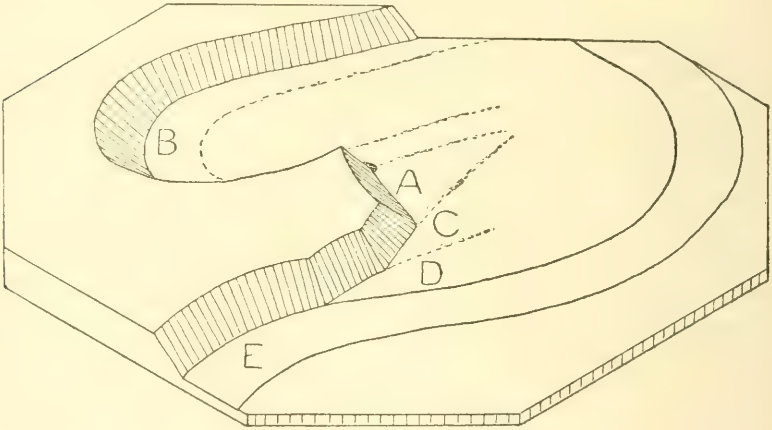


Fig. 32.

Defended Cusps: Later Stage. After a ledge has once been discovered by the swinging river, there is much probability that the forward reach of its under slope will present an obstruction to the stream every time it swings again towards the valley side. For example, let the stream of Figure 31 be supposed to have returned from a swing to the eastern side of its valley floor. It will now be at a lower level than before and will therefore be halted somewhat in advance of the defended cusp previously developed. Figure 33 shows the blunt cusp of a slipping meander thus determined. Another swing out and back having been accomplished, Figure 34 shows the work of a compressed meander, A, which for a time was held up-valley from a third exposure of the long-sloping ledge; but the stream was then withdrawn from its roundabout course by a short-cut, after which a sweeping meander wore out the three short curves, B, down-valley from the ledge; and still later the next down-sweeping meander, C, trimmed off the terrace front close to the ledge preparatory to slipping past the obstacle and pushing still further back the down-valley side of the terrace front. Another stage is shown in Figure 35. Here the eighth westward swing of the stream is recorded (compare Figure 25). Part of the plain formed by the second swing happens to be still preserved, but not of the first and third. All the later swings, fourth to eighth, are well indicated. A strongly-compressed meander of the eighth swing has trimmed off all the terraces a little distance up-valley from their ledges, and would have trimmed them still closer but for being withdrawn by a short-cut. A later meander of the same swing is less successfully wearing away the down-valley extension of the terraces.

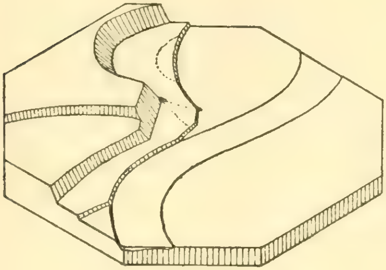


FIG. 33.

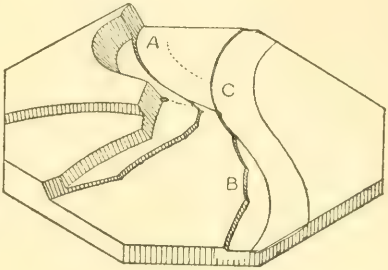


FIG. 34.

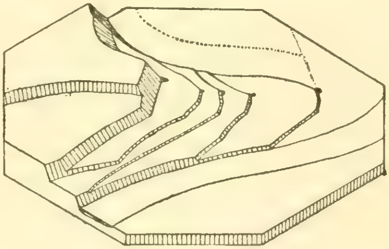


FIG. 35.

It is evident that an infinite variety of terrace patterns may be expected in association with defending ledges; yet they must all conform to certain general laws of development.

If the ledge lies at a low level, the greater part of the terraces that have been cut at swings of higher level will have been destroyed before the ledge has a chance to defend them. If the ledge is of large size, rising nearly to the highest terrace level and standing forward in such a position that the stream may frequently swing against its buried slope, a whole flight of stepping terraces may be not only formed, but preserved by it. Here the early terraces, unlike those of free-swinging rivers, are defended by ledges, and cannot here be attacked by the later swings and sweeps of the stream. They are subject to destruction only by general weathering and washing of the valley sides. It is evidently, then, to the largest and highest and most outstanding ledges that one must go in order to find the fullest record of the number of swings that a river has executed during the excavation of its valley, for only on such ledges are the records of river terracing well preserved. Elsewhere they are for the most part swept away. Even here some swings may not be recorded. In short, the maximum number of terraces shows only the minimum number of river swings.

Diminished Swinging of the Meander Belt. The greater the depth to which the valley floor is degraded, the more frequently may ledges be found, and, as a rule, the nearer will they stand to the axis of the valley. The number of defended cusps will therefore tend to increase as the valley deepens. The breadth of free swinging will at the same time decrease, and the space between the scarps of the lower terraces will necessarily be less than the space between the higher terraces. This principle, first stated by Miller, seems to be essential in explaining the stepping terraces of New England.

It must frequently happen that ledges approach the axis of a valley more closely at one point than at another. The valley may be well beset with buried reefs for a fraction of a mile or more, and then may be relatively free from ledges for several miles up and down stream. Where the ledges are numerous, the valley will be narrowed, and the terraces will be preserved in good number; but in the stretches that are comparatively free from ledges, or in which ledges are found only at low levels, the valley floor may be broadly opened, and but few of the many flood plains that the river there formed at various levels will be preserved. These open basins, often bordered by a single high-scarped terrace, have attracted less attention than they deserve in the discussion of terracing; and well-developed flights of terraces have been given an importance that their restricted occurrence hardly warrants.

Distribution of High-Scarp and Low-Scarp Terraces. Ledges may be gradually disclosed at various points up and down the valley, each one having an effect in cusp-making and terrace-keeping appropriate to its position with respect to the valley axis. The frequent swinging of the meander belt from side to side during the slow degradation of the valley floor requires that the discovery of every ledge lying well within the belt of wandering should be made soon after the stream has degraded the valley floor to the level of the ledge top. If the valley floor is deepened ten feet during a complete swing of the meander belt to and fro, it would be very unlikely that a ledge within the breadth of swinging should escape discovery until the valley floor was worn down twenty feet below the ledge summit. It would be impossible for the discovery to be postponed so long that the stream should first encounter the ledge fifty feet below its top, unless the ledge were situated rather far to one side of the valley axis, where it might not be encountered by the down-sweeping meanders every time the meander belt swung across the valley. The more likely case is that an actively swinging, slowly degrading stream will discover the upper part of every ledge lying well within the belt of wandering, and that thereafter the stream will frequently swing against the slope of the ledge at lower and lower levels as the valley floor is deepened; unless, indeed, another ledge, nearer the axis of the valley, and with a lower summit than the ledge already discovered in its neighborhood, prevents the river from swinging laterally so far as it had at higher levels.

This specialized conception of the terracing process leads to some reasonable deductions as to the distribution of high-scarp and low-scarp terraces. They are summarized in Figure 36. A low-scarped terrace is formed near the western border of the belt of wandering shortly after degradation has begun (see further side of figure). After six swings the river discovers a ledge (also on the further side of the diagram) somewhat within the belt of wandering. Then all the terraces of earlier swings lying back of this ledge will be preserved. On every later westward swing the river is halted nearer and nearer to the axis of the valley. Thus a flight of stepping terraces is formed in connection with a series of defended cusps; but on account of the absence of ledges on the near side of the diagram and of the increased breadth of wandering as the later stage of terracing is approached, the river destroys all traces of the earlier terraces in the foreground, where the tenth swing produces a single scarp by which the highest plain descends to the river level. Then the eleventh and twelfth swings are held off from the high scarp by a lower ledge on whose slope two low-scarped terraces are carved. It may therefore be concluded that low undefended high-level terraces of early swings are most likely to be preserved back of defended cusps of later swings; that the undefended terraces of early swings will probably be swept away in the production of a single high-scarped terrace wherever broad swinging at low levels is not prevented; and that when high scarps occur in a flight of stepping terraces they are more likely to be found at or near the top than near the bottom of the flight.

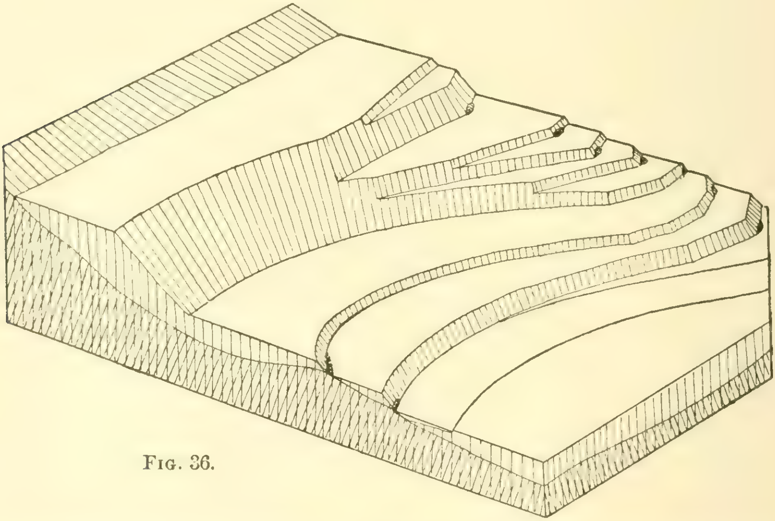


Fig. 36.

Effect of Rock Barriers. Superposition upon strong rock barriers has already been considered on pages 292 and 309, in so far as it determines the separation of a valley into several compartments, in each of which the flood plain is thenceforward graded with respect to the next down-valley barrier. This is a very familiar condition in New England, as the water-power in the falls or rapids on the down-valley side of the barriers has repeatedly determined the location of our manufacturing villages and cities. In the present section, brief consideration is given to the effect of rock barriers in producing a fixed node, as Emerson has called it (736), in a stream that elsewhere vibrates freely as it meanders and swings on its flood plain. It is, however, not yet clear how a wandering stream will behave up and down valley from a fixed node. Several suppositions may be made.

First, the meanders will sweep down the meander belt, and the meander belt will swing to and fro across the valley, but the amplitude of both movements will be decreased as the node is approached, and extinguished as it is reached. So far as my observations go, this condition is more appropriate down-valley than up-valley from a fixed node. Below the node, slight curves may be formed; these may develop into normal meanders, Figure 37 (the river flows to the right), as they sweep away from the sill; but such development will probably be gradual, and hence the valley floor will widen gradually in that direction.

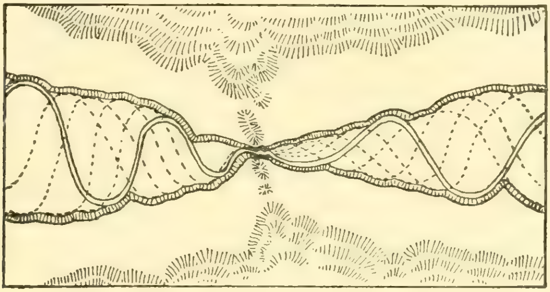


FIG. 37.

Second, the meanders may continue almost in full force as they approach the node from up the valley, merely changing in the lowest part of their course that leads directly to the sill. This might involve the introduction of a "kink" into the meander system, at the point where a change is made from the normal down-sweeping curve to the constrained course that leads to the ledge. That such a sharp bend is possible seems to be shown by certain peculiar forms in the meanders of the Theiss on the plain of Hungary; it being probable that bends of this kind result from the faster down-sweeping of some meanders than of others. The considerable breadth of flood plain often observed next upstream from a node supports this supposition.

Third, the fixed node may perhaps induce the formation of free nodes, evenly spaced from the ledge of superposition; then between the fixed node and the free nodes, the stream might vibrate as a stretched string vibrates when it is lightly "stopped" at a third or a quarter of its length. Symmetrical free terrace cusps would result from this process. So systematic a movement would seem to be possible only in rare cases, if at all; but the terraces of Chicopee river above Beecham Falls, a few miles northeast of Springfield, Mass., give some support to this possibility. Further observation is needed in this direction.

When two barriers occur near together, leaving a free space of half a mile or so between them, the river is fixed at two nodes, but may vibrate between them. A remarkable case of this kind is found in the valley of Saxtons river at Bellows Falls, Vermont, as described on page 337.

Relation of Terrace Patterns on the Two Sides of a Valley. It has been already pointed out as a matter generally accepted by many observers, that the terraces on the two sides of a valley need not necessarily agree in number or in height. The relations of terrace patterns as seen in plan on the two sides of a valley have been less considered. It is desired here to indicate certain relations that seem to obtain in special cases.

When a group of defended cusps occurs in a valley of moderate breadth, the stream must have been repeatedly deflected across the valley by the defending ledges, so as often to impinge upon the opposite side of the valley in about the same place. Hence re-entrants of more than usual size may there be worn out, next up-valley from which a group of free cusps may thus come to stand about opposite the defended cusps. If the meander next above the ledge is somewhat compressed, the stream may strike more squarely across the valley and under-cut the down-valley side of a terrace with somewhat greater vigor than usual. The valley of the Westfield river, a mile or so up-stream from Westfield, Mass., offers some remarkable examples of this kind (page 333).

When a side stream enters the valley of a degrading main stream, it tends to push the main stream away, and thus causes it to wear out re-entrants opposite to the entrance of the side stream. Reacting from such re-entrants, the main stream will strike across the valley and scour out another group of re-entrants below the mouth of the side stream. When this transverse deflection of the main stream is confirmed by the occurrence of a guiding ledge, the re-entrants will be all the more persistently and repeatedly carved out. The Connecticut seems to show an example of double control by the Westfield and by ledges in the southern part of Springfield, Mass. (page 344); and the Westfield itself, two miles east of Westfield village, offers a similar example of double control (page 330).

Ratio of Sweeping, Swinging, and Degrading. The foregoing analyses of the process by which a graded and wandering river may degrade and terrace its valley suggests a method by which a quantitative determination may be made of the ratios of sweeping, swinging, and degrading. If numerous measures are taken of the difference of level between adjacent terraces in a certain section of a valley, it may be expected that two groups of minimum differences should be found; the group of smaller values representing the deepening of the valley floor in the interval between the down-valley sweeping of two successive meanders; the group of larger values representing the deepening between two successive swings of the meander belt.

If measures of this kind were taken in different sections of a valley system, it might be possible to determine from their variations whether an even regional uplift or a tilting were chiefly responsible for the activity of the river in carving its terraces, as the following considerations will show.

In the case of uniform uplift over a large area, let it be assumed that the movement was rather quickly initiated, and then steadily continued until it rather rapidly weakened at its close. We should then expect that the terrace scarp marking the interval between two lateral swings of the meander belt would be of greatest measure and relatively constant in the lower course of the main river; but the slow initiation of the uplift might possibly be recorded by a few low terraces at the top of the series; the slow close of the uplift and the very slow degradation of the valley floor in later time might be recorded by a few terraces of lower and lower scarps at the base of the series. If any terrace in the lower course of the river could be followed up the valley, it would assume a relatively higher and higher position in the series; for when the river had in its lower course worn down its valley floor to a low grade at the close of the period of uplift, there would still be a considerable amount of degradation permitted to the middle and upper part of the river. As a result, the very low terraces at the base of the series near the river mouth might gain a higher rank and a greater scarp height further upstream. If the terraces could be followed up to the headwaters of the river system, they would become narrower and finally disappear in single-scarped V-shaped valleys. So far as they could be recognized, the upper members of a headwater series might correspond in date to the basal members near the river mouth; while the basal members of a headwater series would decrease in scarp-height as they were traced down-valley, until they at last merged in the even flood plain of the middle or lower river course. So many are the irregularities of drift terraces that there has not to my knowledge been any systematic attempt to discover the facts by which these deductions might be confirmed.

In the case of a tilting, with fulcrum at the river mouth and at right angles to the general river course, the maximum height of two-swing terrace scarps would be found somewhere near the middle course of the river; and the scarp height would thence decrease down-valley and up-valley. It seems that, in such a terrace system as that of the Connecticut, it may be possible to apply this test and thus gain from the dimensions of the terraces a direct proof as to the kind of movement by which the work of terracing was initiated, as well as a confirmation of the evidence already in hand regarding the nature of postglacial movement in the New England province.

RELATION OF THE PRECEDING DEDUCTIONS TO THE OBSERVATIONS DESCRIBED IN THE FOLLOWING SECTIONS. The facts presented in the following sections are chiefly details of structure and form, directly observable; changes of form are occasionally noted, but these are of relatively small measure. All these details are but the present members of a long series of facts, every one of which might have been recorded, had observers been living to witness them; and then the origin of terraces would be fully understood. But the earlier members of the series are hopelessly lost to observation from being prehistoric. In their unavoidable absence, theory attempts to supply a series of conditions, pictured by the reasonably guided imagination, which shall imitate the series of past facts, and thus, as it were, call them to life, bring them into the field of vision. The success of the theory is not to be measured so much by the apparent reasonableness of its fundamental suppositions, or by the definiteness with which various imaginary consequences may be deduced from it, as by the accuracy with which the observable members of the deduced consequences imitate the facts of actual occurrence. The greater the number of peculiar categories of observed facts, the greater the probable correctness of a theory whose deduced consequences can match all of them. Hence the importance of minute observation and careful generalization on the one hand, and of accurate and detailed deduction on the other. Hence also the importance of carefully distinguishing these unlike processes in order that their results may be systematically confronted in an unprejudiced comparison. The elaboration of the deductions in the preceding sections therefore seems to be as necessary a part of the study of terraces as is the accumulation of observations for presentation in the following sections.

The theory of terracing has here been presented before the observations of terraces are detailed, because it is the theory with its deduced consequences and not the facts that are on trial. Furthermore, it is only after the presentation of the theory that the pertinent facts can be conveniently selected from among many others and that their bearing can be clearly appreciated. True, the attempt might be made independent of any theory to observe all facts thoroughly and to record them minutely, in the hope of including every item that could be asked for in the testing of whatever theory should afterwards be invented; but under this method of work, items of minor importance are confused with those of major importance, and their recital becomes so long that the beginning is forgotten before the end is reached. As a matter of fact, observational study of this kind is notoriously incomplete. Indeed, the terrace problem, like many others, gives striking illustration of the difficulty if not the impossibility of really seeing all the essential facts when only the eyes of the observer are trusted; and it illustrates at the same time the critical power that is given to observation when it is directed towards significant points, instead of being allowed to wander in the vain hope of finding all the facts before theorizing is begun. For example, if it is not already manifest from the deductions of the preceding paragraphs that the terrace spurs formed of grouped cusps and the outcropping ledges that are associated with them are of particular significance, no doubt will remain on this point when the observations detailed in the following paragraphs are reviewed; yet in all that has thus far been written on this subject in New England, no description of grouped cusps is to be found, and no recognition of the significance and the generality of the relation between ledges and cusps is recorded. It is as if it had been thought that all parts of a terrace are equally significant; that when ledges appear at the terrace base they are of no particular importance. Even the citations made above from the writings of Edward Hitchcock do not show that that careful observer thought the ledges he described were of any more than local importance; and certainly no later observer has been led by Hitchcock's essay to understand the control that ledges exercise in determining terrace pattern and terrace preservation. Yet after apprehending this control and discovering the suggestive relation that must obtain between ledges and cusps, the observer no longer strays over his field; he directs his steps and secures in the least possible time the greatest possible results.

Largely deductive as the preceding portion of this essay is in its present form, the reader should not suppose that it was prepared independent of observation. The actual progress through the problem has involved repeated alternations of external and internal work; the collection of observations and the induction of generalizations on the one hand; and on the other hand the invention of hypotheses, the deduction of their consequences, the confrontation of deductions with generalizations, the evaluation of agreements, and the repeated revision of the whole process. It is not profitable to expose the personal history of a study all through these stages, for the convenience of the reader is best served by a careful separation of its two phases; and to the second of these we may now turn in Part IV. with no more delay than is required for the citation of the following pertinent extract from Playfair's Illustrations of the Huttonian Theory of the Earth. After pointing out that to wait for the completion of discoveries in other sciences before theorizing in geology "would not be caution, but timidity, and an excess of prudence fatal to all philosophical inquiry," this lucid writer of a century ago proceeds as follows: —

"The truth, indeed, is, that in physical inquiries, the work of theory and observation must go hand in hand, and ought to be carried on at the same time, more especially if the matter is very complicated, for there the clue of theory is necessary to direct the observer. Though a man may begin to observe without any hypothesis, he cannot continue long without seeing some general conclusion arise; and to this nascent theory it is his business to attend, because, by seeking either to verify or to disprove it, he is led to new experiments, or new observations. He is also led to the very experiments and observations that are of the greatest importance, namely, to those *instantiæ crucis*, which are the *criteria* that naturally present themselves for the trial of every hypothesis. He is conducted to the places where the transitions of nature are most perceptible, and where the absence of former, or the presence of new circumstances, excludes the action of imaginary causes. By this correction of his first opinion, a new approximation is made to the truth; and by the repetition of the same process, certainty is finally obtained. Thus theory and observation mutually assist one another; and the spirit of system, against which there are so many and such just complaints, appears, nevertheless, as the animating principle of inductive investigation. The business of sound philosophy is not to extinguish this spirit, but to restrain and direct its efforts" (524, 525).

IV. Observations of River Terraces in New England.

VALLEY OF THE WESTFIELD RIVER, MASS. *Eastern Section.* This branch of the Connecticut rises among the hard-rock Berkshire hills of western Massachusetts, the round remnants of the uplifted and dissected Cretaceous peneplain of the Appalachian province, and thence flows eastward part way across the broad valley lowland that has been excavated in the weaker Triassic formation during later Tertiary time. Between the eastern base of the crystalline uplands and the ridge formed on the main sheet of extrusive trap within the Triassic area, the stream has excavated a fine series of terraces in the unconsolidated drift deposits that have been so abundantly spread over the Triassic lowland by the Connecticut and its tributaries.

The village of Westfield lies near the middle of this terrace system and serves to mark the separation of its unlike eastern and western divisions. In the eastern division, Westfield river, re-enforced by Little river, a branch which leaves the hills two miles south of the main stream, has opened a broad basin at an elevation of about 140 feet. The basin floor is nearly everywhere enclosed by the strong scarp of a single high terrace whose plain stands at altitudes of 240 to 280 feet. The plain is not of simple origin. On the southeast, its surface is rolling, as if consisting of morainic and kame-like deposits. On the north, it is smooth and its sands are fine enough to have been raised in occasional dunes; here the plain falls off southwestward to the valley of Powdermill brook in a series of lobes, whose intermediate depressions are too large to have been excavated by local drainage: hence it is probable that this part of the plain is a delta front in one of the areas of deposition described by Emerson (650–653). South of the main basin, the smoother part of the high plain (Poverty plains) is regarded by Diller (265) as an extension of the plain on the north; the originally continuous surface having been formed by the flooded Connecticut. Westward up the Westfield valley, the high plain ascends towards the hills and is of much coarser materials than elsewhere; this part seems to have been capped by the local outwash from the high ground during the period of aggradation. As the coarse upper gravels lie on fine sands and silts, this high plain is probably, like the one on the north, a delta surface, built up in standing water.

The strong scarps, B, Figure 39, by which the high drift plains descend to the main low-level basin, everywhere present concave re-entrants, whose curves unite in cusps — usually two-sweep cusps — of greater or less acuteness; and this shows that the streams have repeatedly swung against the terrace scarp, under-cutting it and pushing it back, after the present grade had been essentially reached. The curved re-entrants are of somewhat larger radius on the north than on the south, as if they had been scoured by the Westfield and Little rivers, respectively. With the significant exception of certain points on the east and west, to be described below, all these cusps, at least twenty-four in number, are free, undefended by ledges. We have, therefore, here an example of a vigorous stream with a good-sized branch working in a broad deposit of loose drift, and free to sweep, swing, and wander over a large area. A late stage of terracing has been reached, for the wide plain is nearly or quite reduced to grade with respect to a relatively permanent local baselevel in the trap-ridge notch on the east. The detention of further degradation by the trap barrier is a factor of importance; for many recent swings of the streams must have on this account tended to destroy earlier terraces by reducing them all to one level, instead of tending to make new ones at lower levels. Whatever flood plains may have been produced during the excavation of the present basin floor, the streams have now so well taken advantage of their opportunity for lateral corrasion or "sapping" that terraces at high and intermediate levels are nearly everywhere obliterated, and even the low terraces are as a rule destroyed by the broad swinging of the streams at their present grade.

Westfield river is at present nowhere working against the base of the high terrace on the north; its actual course lies about half a mile to the south of the scarp, but several of its former courses along the terrace base are clearly revealed in a series of shallow swampy troughs, the remains of channels from which escape seems to have been effected by repeated short-cuts or cut-offs. The river is now engaged at several points in grading down to modern flood-plain level a broad and low terrace, parts of which are not yet destroyed.

Little river was in 1901 sweeping against its high terrace on the south at two points a little east of the New Haven and Northampton Railroad. Here the usual cover of vegetation has been removed from the scarp, the sands are under-cut, and the face of the scarp is sliding intermittently into the stream. Small sand dunes are formed at the top of the sliding bank by the northwest winds which sweep the sand up from below. It is evidently enough by a repetition of sweeping and swinging of this kind that the high terrace has been worn back to its present outline.

Where the rivers have withdrawn from the high-scarped terrace, flat fans have been formed at the outlet of the minor lateral valleys of small brooks, or beneath little gulleys of wet-weather wash. The fan of Powdermill brook, for example, forms a low barrier, X, Figure 39, across a deserted channel of Westfield river, and thus determines a swampy depression just northeast of Westfield station. The further course of the brook follows the marshy deserted channels of Westfield river at the base of the scarp for over a mile.

It would be difficult to find better illustrations of the deductions presented on page 310 than are offered by this beautiful basin. The two chief streams, far from exhibiting any incapacity to open their valley floors, have now widened them to a greater breadth than ever before. Whatever decrease of capacity may be due to decrease of stream volume and of stream slope, and whatever increase of work may be due to the more active wash of side streams on account of gain in height of valley sides, the main streams are certainly more competent to corrade laterally now than they have ever been, and there is every probability that they will in the future continue to widen their basin still further by intermittent attacks on its border until restrained by defending ledges or by the hand of man. Indeed, so nearly complete is the obliteration of all terraces above the level of the present basin floor, one might be tempted to conclude that the Westfield and Little rivers never produced any extended series of flood plains in this division of their course at higher levels than those of modern times, until an examination of the western division of the Westfield terraces proves that flood plains must have been produced at various levels in the eastern division as well as elsewhere.

Evidently then, as far as this example goes, it affords no evidence that the production and preservation of terraces is due to any incompetence arising from decrease in the volume or from other changes in the habits of our New England streams. Terrace preservation must be due to some control external to the streams; and of this we find immediate proof on looking at the eastern and western enclosure of the broad basin just described.

The basin is enclosed on the east by the approach of a defended spur, A, Figure 38, on the north towards a free spur, B, on the south, beyond which a subordinate basin, C, is again opened. The defended spur carries a terrace plain at a height of 200 feet, and the highest plain rises further north by a faded scarp of gentle slope. Sandstone ledges are abundant along the western base of the spur; they are unusually steep, in part because of the eastward dip of the strata, and in part because of a certain amount of under-cutting by the Westfield when it ran beneath them. The eastern side of the spur is not trimmed close to the defending ledges, but illustrates the unsymmetrical relations shown in Figure 31. Widely as the river has swung from side to side in the basin further west, it was here strongly constrained. Not only so: Westfield river has been somewhat impelled northward by the entrance of Little river from the south (west of the area shown in Figure 38); and it is probably in part at least on this account that the basin has been so well broadened northward; yet on every sweep or swing against the sandstone reef, the river was not only restrained from further northward conquest at that point, but was deflected obliquely southward across the valley. It is very probable that the excavation of the subordinate basin, C, is due to this cause, for it is opened further to the south than to the north. Three strong southward loops of the river, D, E, F, (including the present one) are here recorded; and it can hardly be by chance that the river has thus

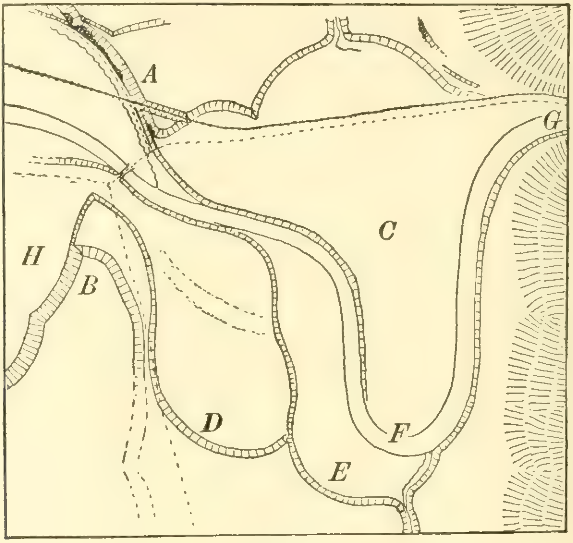


Fig. 38.

repeatedly turned southward on its way to the fixed node, G, in the trap-ridge notch.

Nearly opposite to this well-defended spur, but a little further westward, the free spur, B, rising to the full height of the drift plain, separates the subordinate eastern basin, C, and that part of the main basin, H, which has been scoured out chiefly by Little river. Unlike the defended spur on the north, the free spur is not a relatively permanent feature of the valley; it will be removed without difficulty if Little river takes a fancy to trim away its western base. Nevertheless, its occurrence to-day does not appear to be altogether a matter of chance, for it seems to illustrate the systematic features described on page 322.

The main basin is enclosed on the northwest by a well-defended spur, known as Prospect hill, A, Figure 39, just west of Westfield station; this will be further described with the terraces of the western division of the valley. On the southwest, Little river is held from swinging at present levels by superposition on a transverse sandstone ledge, to which brief reference will be made further on. The contrast between the openness of the main basin, excavated where the streams have not been restrained by ledges, and the narrowness of the entering valleys where ledges have been encountered, is most striking.

Western Section. The western division of the Westfield terraces, occupying the valley for about four miles from Westfield village to the base of the hills, is of greater interest than the eastern, inasmuch as it preserves the records of river work at many levels between the highest and the lowest plains. I have prepared a somewhat detailed account of it for publication in the "American Journal of Science," and hence shall here refer only to such features as confirm the deductions of earlier paragraphs.

The chief features of this interesting locality are shown in bird's eye view in Figure 39, as if looking northeast from a height of several thousand feet above the left front corner of the diagram. The Boston and Albany railroad runs through the view for a distance of about a mile and a half; the foreground scale is larger than that for the background. Heights are exaggerated. Outcropping ledges are black.

From Westfield to a small rural settlement known as Pochassic Street, two miles to the west, many small ledges are exposed, and many stepping terraces occur along the northern side of the valley. Few ledges are seen on the southern side, and there the valley is generally bordered by a strong upper terrace, with a few low terraces beneath it. On the northern side there are four groups of defended terrace cusps, forming what may be called the Pochassic (just to the left of Figure 39), Perry's, K, Brown's, F, and Prospect spurs, A, while curved re-entrants have been excavated between the spurs where ledges are rare or wanting. The re-entrants show that the river has everywhere attempted to widen its valley, while the terraces on the defended spurs show that the widening has been locally prevented by the outcropping ledges. Wherever free cusps occur they exhibit the patterns deduced as of common occurrence on page 308. None of the combinations there deduced as rare are found. The cusps are usually more closely trimmed on the up-valley than on the down-valley side. It would be difficult to imagine a more complete confirmation of Miller's theory than is here presented.

Special mention may be made of a few features. Just east of Pochassic Street a series of at least nine terraces, H to M, may be counted. They range in height from eight to fifteen feet, and thus suggest a rough measure for the amount of valley deepening during a swing of the river southward across the valley and back again. This maximum number is evidently dependent on the numerous ledges here discovered at all levels from highest to lowest. Although no other part of the valley shows so many terraces, it must be concluded that flood plains, continuous with the remnants here preserved, were made far up and down the valley; and hence that the river was essentially at grade during the whole process of valley degradation. Two terraces at the top of this flight, in the re-entrant east of Pochassic Street, exhibit minor re-entrants of small radius and large arc near H and H′, comparable to the curves of the present river, thus indicating that no significant change of volume has occurred since the work of terracing began. A broad terrace plain stretches back of Perry's spur, K, and four low terraces rise above it to higher levels, showing that four broad northward swings were here executed. The fifth terrace (counting from the top of the series) runs forward to Perry's spur, because the highest ledge of that spur was discovered when the river was making its fifth northward swing. It is worth noting that several defending ledges in this spur would be unseen but for road and railroad cuts. The fourth terrace swings forward in a long sweeping curve to the apex of Brown's spur, because the summit ledge was there found by the fourth northward swing. Only two distinct terraces occur on the high plain back of Prospect spur, because the ledges in that spur rise still higher than in Brown's spur. In a word the river has always shown a capacity for broad swinging until it became hampered in its movements by coming upon previously buried spurs. Brown's spur is peculiar in being closely trimmed on the down-valley side as well as on the up-valley side. Prospect spur has a terraced re-entrant, C, scoured out at mid-height with small radius and large arc, far back on its up-valley side; that is, a meander of the river has there been twice compressed against defending ledges, after the style of Figure 30. Elsewhere the meanders seem to have slipped past the defending ledges, after the style of Figures 25 to 28.

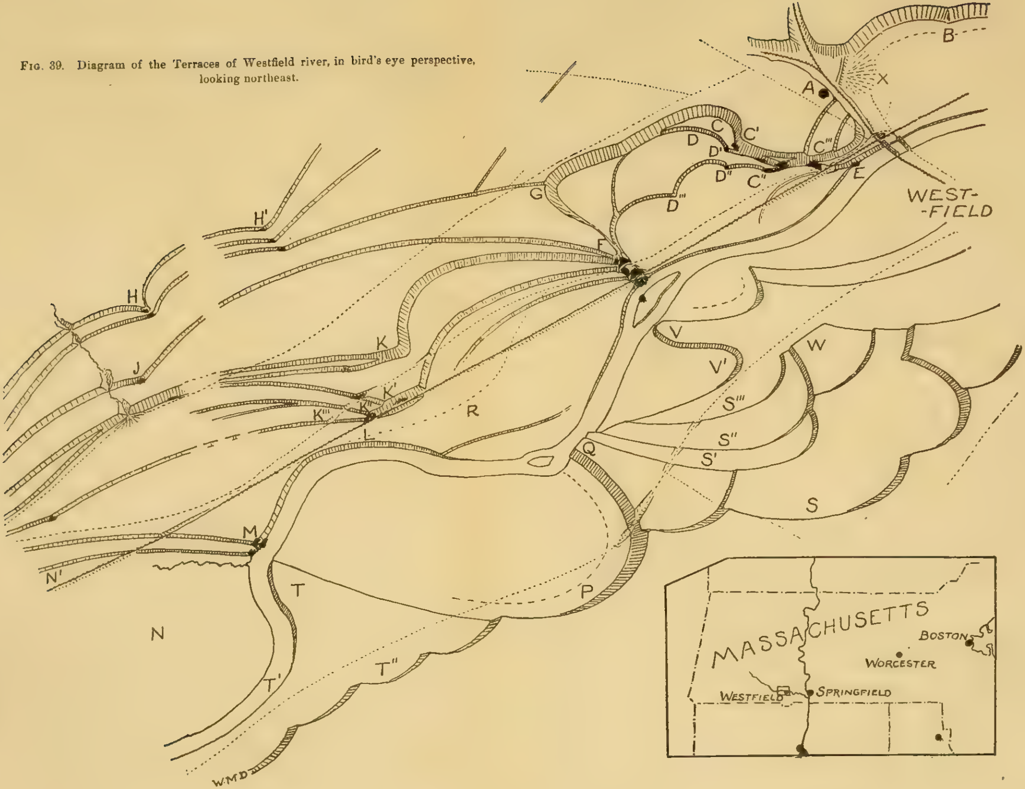
The terraces on the south side of the valley are in several cases determined indirectly by the ledges on the north side. This is most distinctly the case where the river formerly swept forward from the lowest and furthest forward of the Pochassic ledges, M, and consequently cut out one of the deepest re-entrants on the south side of the valley, P. A single scarp now descends from the high-level plain into this strong recess. Similar but less manifest relations are suspected elsewhere; thus K′, K″, K ″ on the north may correspond with S′, S″, S‴ on the south. Conversely, a number of low-level terraces remain on the south side of the valley south of Brown's spur, perhaps because the repeated northward swings of the river into the largest northward re-entrant, that between Brown's and Prospect spurs, have not required their removal. The numerous free cusps here found exhibit the features already deduced as of common occurrence. It is intended to make a close measurement of the slopes of these terrace plains in the hope of correlating the now separate remnants of single flood plains, and thus tracing the history of the terracing process in some detail.

LITTLE RIVER. A few words may be said about Little river, although the southern side of its valley has not been closely studied. The valley of this stream is divided into three sections by two barriers of sandstone, next up-stream from which are considerable bodies of till. The till has been cut down to grade with the sandstone barriers, but the valley in the till is held to a small width, practically without terraces. Relatively few terraces are found even where the valley is bordered by stratified drift. In explanation of this it should be noted that Little river is smaller than the Westfield, and that a small stream must be hurried in attempting to keep pace with the degrading action of its master. Hence the smaller stream will have little opportunity for lateral swinging and terracing so long as it runs through loose drift to a more actively degrading master stream. There are two conditions under which opportunity for lateral swinging will be presented to the smaller stream. First, when the master stream has effectively ceased degrading its valley. This is now the case with the Westfield, because it has cut down upon a hard-rock barrier in the trap-ridge notch; and it is probably for this reason that the lower section of Little river has swung so broadly and opened the extensive valley floor already described as forming the southern part of the open basin east of Westfield. Naturally enough, then, the enclosure of the broad valley floor on the south — where Little river is alone responsible for the form of its border — is nearly everywhere a single high-scarp terrace with numerous one-sweep or two-sweep cusps. In other words, Little river is swinging on its present flood plain more broadly than it has at any earlier time during the process of degradation. Second, whenever the smaller stream becomes superposed upon a rock barrier, its work in the next up-stream stretch proceeds at its own rate, entirely independent of that of the master stream. Hence the valley floor in such a stretch tends to widen and thus to under-cut all the narrower flood plains formed in earlier stages of degradation. This is the case with both the second and third sections of the Little river valley. It has a well-opened valley floor usually enclosed by single terrace scarps that rise to the full height of the upper plain, so far as I have followed them. The simple scarps have well-developed re-entrants and cusps, showing an active lateral swinging of the stream at present grade, but not giving indication of an equivalent swinging at any higher flood-plain level, and hence not giving support to the opinion that the river is to-day of an enfeebled constitution.

VALLEY OF SAXTONS RIVER, VERMONT. Saxtons river enters the Connecticut from the west at Bellows Falls, Vermont, and shows a beautiful variety of terrace forms for some three miles above its mouth. Figures 40 and 41, separated by an unrepresented interval of about half a mile, give rough illustration of these features. Careful survey would undoubtedly show that the sketch-maps need many changes in details, but it is believed that the relative positions of terraces, with their free and defended cusps, are shown with sufficient accuracy for the purposes of the present discussion. The chief points here illustrated are as follows: —

Western Section. In the up-stream or western section, Figure 40, there are numerous ledges, but none of them have acted as local base-levels. The present valley floor is graded with respect to a heavy rock barrier a little east of the limit of Figure 40, and at the western border of Figure 41. In the three strong ledges, M, Q, R, Figure 40, on the north side of the valley, the rocks are schists, with strong dip to the northeast, and hence with bold outcrops to the southwest. The stream

Fig. 39. Diagram of the Terraces of Westfield river, in bird's eye perspective, looking northeast.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WORCESTER
WESTFIELD
SPRINGFIELD

has swung against the steep face of these ledges, sweeping them practically free from drift on the up-valley side down to modern flood-plain level, but fine flights of stepping terraces are preserved on the down-valley side of each ledge, where the trailing remnants of successive flood plains have been defended from stream attack. At least ten different terrace levels can be counted adjoining ledge M. The third and fourth levels from the top are pleasantly shaded by a pine grove, and are used as a picnic ground, access to which is conveniently given by an electric railroad on the valley floor. Some of these terraces may have been carved by a small stream that here enters from the north, but in any case they have all been developed with respect to graded flood plains of the main stream. Their vertical interval ranges from five to ten feet, which may be taken here, as in other cases, to represent the amount of deepening that the valley floor suffered between two northward swings of the stream. The value of the ledges is most manifest; they defended the upper terraces from being consumed when the lower terraces were cut by the returning stream.

Ledges Q and R present similar features in flights of eight and six steps respectively. The river is to-day swinging vigorously against the base of ledge M. The modern flood plain reaches the base of Q and R, and is opened northward between M and Q in a space that seems to be comparatively free from ledges. The ledges here outcropping on a low terrace at N and O seem to have served the double purpose of stopping the northward swinging of the main stream, and of limiting the east and west swinging of the side stream at that level. I have not closely examined the terraces up-valley from M, but at least one of the blunt cusps there seems, when seen from the terrace on the opposite side of the valley, to be defended by a ledge at present flood-plain level. Down-valley from R, the valley side is heavily wooded for quarter of a mile. Then it closes in as numerous ledges and boulders make their appearance about S, near the main road bridge.

Low-scarp terraces are wanting at high levels on the south side of the valley. The upper plain descends by a single strong scarp, twenty feet or more in height. It presents a number of sweeping re-entrants between the defended cusps, A, B, C, D, and E. The A-B re-entrant is floored by a rather uneven plain in which several indistinct terraces have been cut on what seems to be at least in part a mass of till, for large boulders are seen thereabout; and this plain is cut off in front by two terraces, whose blunt cusps from F to G appear to be in part determined by ledges, in part by boulders. The small tributary stream that crosses this re-entrant from the south has formed a fan on the high terrace plain and again on the floor of the re-entrant, but it is now dissecting the fans. No B-C re-entrant has been carved out, perhaps because till was there discovered. Several ledges were encountered at lower levels between G and H, against all of which the stream has swung most faithfully. The valley floor would surely be wider to-day, had these ledges not existed. A fine re-entrant was swept out between the defended cusps C and D, when the river ran at a height about ten feet over the modern flood plain, and another effort was here made to widen the valley floor at its present level, but as ledges are now discovered at H and J, farther forward than C and D, the lower re-entrant has not quite consumed all of the earlier flood plain. A low terrace, caught on ledges J and K, stands in front of the re-entrant between D and E. The projection of the strong but low cusp at J as compared to that of the blunt but high cusp at D is one of the best illustrations of the effect of ledges that is found in this little valley. The river must have slipped past the ledge at D, as well as past most other defending ledges hereabouts; but a compressed meander must have been caught for a time on the ledge at J. Down-valley from E, a modern swing of the stream has under-cut all the earlier terraces, and a full-height scarp is the result.

These terraces are even better than those of the Westfield for purposes of field illustration, inasmuch as defended cusps here occur in abundance on both sides of the valley. The narrowing of the interscarp space, as the valley floor was degraded to lower and lower levels, is manifestly due to the presence of the ledges. That the river was continuously acting as a graded but degrading stream is sufficiently proved by the fine flight of stepping terraces at M. That the preservation of the successive terraces is not due to any shrinking of the stream from its first intention as to valley widening, is proved by the vigor with which it has opened the modern flood plain to as great a width as the numerous ledges permit.

It was on seeing — in October, 1900 — the relation of the defended cusp of the little terrace at F to the corresponding defended cusp of the next higher terrace a little farther back at A, that the value of ledges in determining terrace pattern and in preserving the upper terraces from later attacks of the stream first came to my mind. The manner in which this explanatory idea first took shape was as good an example of the sudden invention or birth of theory as I have ever experienced, for the theory was essentially complete at the moment of its first conscious appearance; since then it has only been confirmed by finding that it had already been born to Miller, and by deducing its more minute consequences as presented in Part III. of this essay in order to confront them with numerous examples of actual terrace forms, some of which are described on these pages.

Eastern Section. The lower stretch of Saxtons river, Figure 41, gives beautiful illustration of terraces produced by a stream that has oscillated between two fixed nodes. At the upper node, the stream is narrowly held by ledges at A and G. A little further up-stream is a rocky gorge with cascades, from which the stream is diverted for water-power. The lower valley becomes somewhat more open as the space widens between the ledges B, C, on the south and J-H, L-K, on the north. The small re-entrants between these ledges nearly everywhere bear the marks of having been energetically swept back as far as possible by the stream at various levels during the erosion of the valley. The stream has swung northward at least nine times on the J-H group of ledges, and southward at least seven times on the B group, where till seems to supplement the restraint of rock.

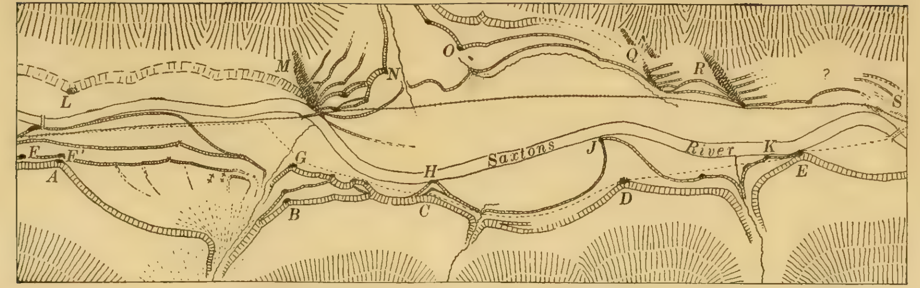
On leaving the cascade and the rapids below it, the stream has graded its course with respect to the eastern rock node between M and F-E; none of the ledges encountered on the way have had other effect than in limiting the breadth to which the successive flood plains have been opened during the degradation of the valley. That the degradation was gradual, giving the stream abundant time for broad swinging and wandering, right and left, is abundantly proved by the terrace remnants of flood plains at various levels.

Passing the narrows at C, L-K, there is a broad stretch comparatively free from ledges until the heavy ridge of rock, M, F-E, is encountered close to the junction of Saxtons river with the Connecticut. The ridge is now cut through by a narrow gorge, with falls on the down-stream side where the road and railroad bridges cross the stream: whether this gorge is entirely the work of postglacial time, I cannot say.

An oval plain, known as the Basin farm, has been opened between the upper and lower narrows, its smooth fields uniting with the curving terrace scarps in a most graceful and pleasing landscape. The Basin plain probably had twice as great an area at the level of its mid-height terraces as it now has at the level of the modern flood plain; but this reduction of area is not to be wondered at, in view of the increasing constriction imposed upon the swinging stream by the mutual approach of the ledges C and K as lower and lower levels were reached.

A few special features deserve mention. A southward deflection of the stream from ledge K, and an increasing southward meander of the stream in consequence of this deflection, with a southward swinging of such a meander, has probably been responsible for some of the large re-entrants on the south side of the basin; but it is not yet apparent why the re-entrants on the north should have been repeatedly worn farther from the line between the nodes than on the south. The various combinations of two-sweep cusps in the group of nine stepping terraces next down-valley from ledge C is in every respect confirmatory of the deductions (page 309). It is notable that remnants of terraces at intermediate heights form little recesses in the cusps of later origin, as might have been expected. The terraces in the wooded slope south of C have not been traced out; but a little farther east four low-scarped terraces rise at D above the plain that forms the top of the nine-step flight, thus making a series of thirteen steps. Curiously enough, these four upper terraces, forming the upper members of the longest flight that I have yet counted, swing northeastward from what seems to be a free cusp, thus apparently imitating conditions similar to those of Figures 15 and 17. No ledge is visible in the front of this group, but as the scarp of the ninth terrace, here descending to the seventh, also bows a little forward directly in front of the apparently free cusp, I am much inclined to think that there is really some defence here, now masked by a slipping drift cover. A soil augur test is proposed to settle this doubt. A detailed map of this basin and its terraces would be well worth preparing.

THE CONNECTICUT BELOW BELLOWS FALLS, VERMONT. The Connecticut river at Bellows Falls is superposed on a large body of rock, on whose down-valley side the river is narrowed in rushing cascades and rapids. A mile farther down-stream, three fine terraces are developed at A, Figure 42, on the west side of the valley just below the mouth of Saxtons river, S, and all seem to be defended by ledges; the upper two by ledges of the large rock ridge at the mouth of Saxtons river (these are marked N, in Figure 41), the lowest by a ledge that stands several hundred feet farther forward and is seen in the railroad cut a quarter of a mile south of Saxtons river. This group of terraces is shown as seen from the southeast in Figure B, Plate VIII., of Russell's "Rivers of North America." A little further south, the two lower terraces are cut away westward in the formation of a broad valley floor, B. A full-height scarp rises at the back border of the floor, and near its middle is a blunt cusp determined by a strong ledge. The southern end of this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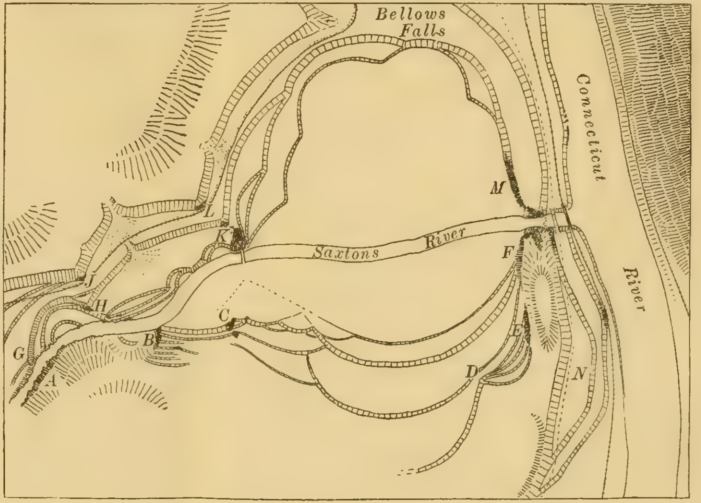
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Figs. 40 and 41. Portions of Saxton's river valley, Vermont.

Scale, about four inches to a mile.

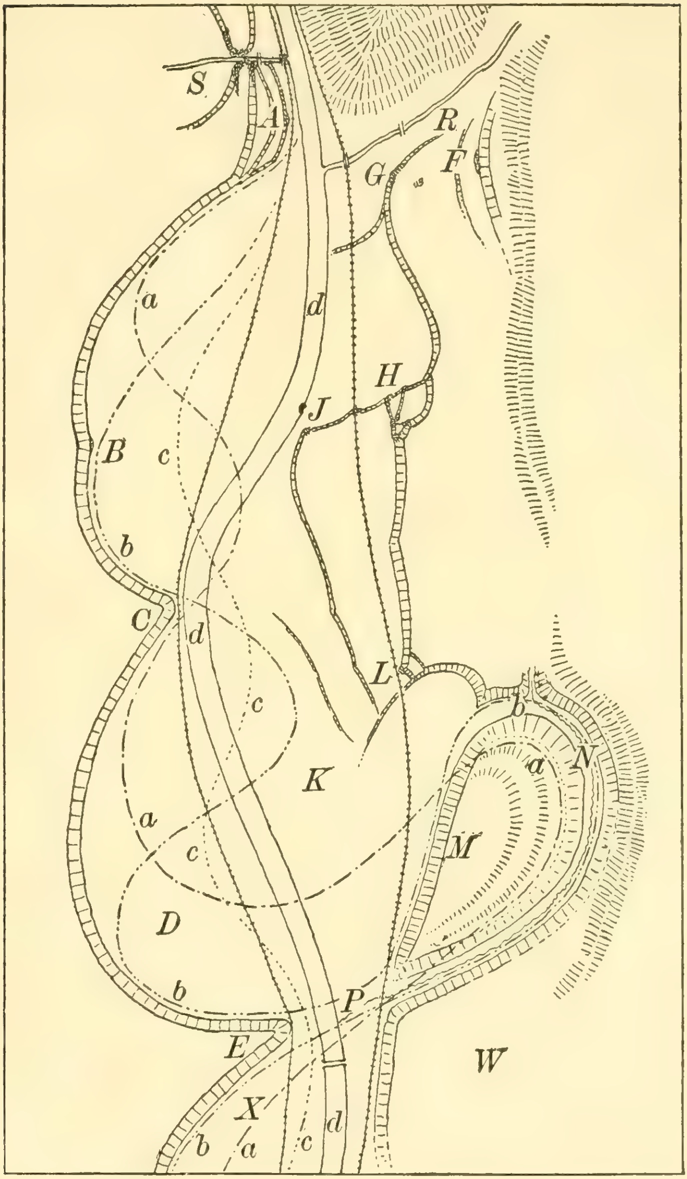
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FIG. 42. The Connecticut Terraces from Bellows Falls to Walpole. Scale, about an inch and a half to a mile.

open section of the valley is enclosed by a high free cusp, C, at whose apex the river is now working. Another open valley floor, D, follows the free cusp, and is limited by a second free cusp, E, of less height but of greater forward reach than the first. The meaning of these two free cusps will be considered below.

Returning to Bellows Falls and following down the east side of the valley past the entrance of Cold river, R, from the northeast, ledges are found to be more numerous. A broad mid-height terrace was opened until a ledge, F, was discovered in the base of the uppermost terrace just south of the Alstead road; the further southward extension of the high terrace has not been followed. The mid-height terrace, followed by the upper north-and-south road, was cut back by a much later swing of the river near present flood-plain level, until a high ledge, G, was discovered an eighth of a mile south of Cold river: the lower north-and-south road skirts its base. Nearly a mile further south is a group of admirably defended terrace cusps, H, up-valley from which the river has swept out some vigorous curves, and on one of which — where the mid-height terrace first advances near the Fitchburg railroad — the river was nearly superposed; the rapids that occurred here for a time were abandoned as the river slipped off the northwest slope of the ledges. Near this point the lower terrace advances to the river bank, on account of the farther forward reach of other ledges, J; one of them now outcrops in the river bank and thus insures the enduring protection of at least part of the low plain on which the railroad is here laid.[1] It is thus evident that the meander belt of the river has here been constrained to take a more and more westward course as it cut deeper and deeper; and it is probably on this account that the first large western re-entrant below Saxtons river has been so thoroughly scoured out at a low level.

The lower eastern terrace is gradually cut back down-valley from the foremost defending ledge; and a broad low plain, K, is thus opened to a half-mile width, after which it narrows towards the bridge between Walpole (W) and Westminster (X). The mid-height terrace continues down-valley from the abandoned rapids, first showing an apparently free two-sweep cusp; then a defended cusp, L, the defending ledge of the latter being disclosed in a shallow railroad cut at the base of the terrace; after this the terrace is cut some distance back in a low-level re-entrant enclosed by a scarp concave southward or down-valley. A little farther on, an isolated hill, M, traversed by the main valley road and crowned by a mansion, is separated from the main slopes of the eastern side of the valley by a deep trench, N, of large sweeping curvature to the northeast and for the most part apparently cut in till. The trench has a rather strong under-cut slope on the outer side of its curved course, and a gently terraced slope on its inner side. There can be no doubt that it marks a former path of the river around a lobate spur, and that the river was diverted from the trench at a comparatively modern, though unrecorded, date by wearing through the narrow neck of the spur at P, a little up-stream from Walpole bridge. The second one, E, of the two free cusps above mentioned on the west of the river is the unconsumed remnant of the neck of this spur, west of the cut-off; the isolated hill, M, is the terminal part of the spur northeast of the cut-off. The following explanation of the relation between the two free cusps, C and E, may be suggested.

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[1] The shading to indicate a low terrace along the east bank of the river is accidentally omitted in Figure 41 for three-fourths of an inch up-stream and half an inch down-stream from J.

At an early stage of the time during which the river was making its great northeastward détour around the spur, EM, its course may be represented by the curve, a, a, a, a. The normal order of change in these curves would develop a later course, b, b, b, b; thus opening out the two large westward re-entrants, B and D, and leaving the free cusp, C, as yet unconsumed between them. Had this process been normally continued, the free cusp, C, would have been in time worn away by the down-valley sweeping of the first b meander; but before this was accomplished, the cut-off occurred at P. Now it may be shown by a study of the detailed maps of the Mississippi River Commission that when a cut-off occurs, a systematic series of changes is initiated, and that these changes are extended up-stream as well as down-stream from the cut-off. The essence of the changes is such that the straightening of the course at the cut-off tends to straighten it elsewhere also, and that this tendency is most active near the cut-off, and weakens with distance from it. Following this principle, the course, b, b, b, b, will be changed to c, c, c, c, and to d, d, d (the present channel). The river will thereby be withdrawn from both of the westward re-entrants, around whose up-valley curves it was probably flowing when the cut-off took place. Thus the free cusp, C, will be left unconsumed for a time at least. It may perhaps be possible, by accumulating other examples of changes similar to this one, to give some degree of verity to the rather hazardous explanation here offered.

THE CONNECTICUT BELOW TURNERS FALLS, MASS. My field notes here are hardly of sufficient detail to serve as the basis of a sketch map. Suffice it to say, that for several miles down the river from Turners Falls to the Fitchburg railroad bridge in Montague, there are numerous examples of defended terraces, fully confirming the principles already illustrated and suggesting some new ones, to which I hope to return in a later essay. But concerning a stretch of the river southward from this section, Emerson has written as follows: "The subsidence of the waters of the Connecticut lakes to the present Connecticut river was very rapid. . . . As a result, one goes down — through the whole length of the Montague Lake, which was well filled up in the flood time, except in its southern portion — by a great scarp to the series of erosion terraces of the modern river, the highest of which rise but a few feet above the level of the flood plain" (725).[1]

This conclusion as to the "very rapid" change of level by which the erosion of the present valley floor in the former drift filling was initiated seems to be based entirely on the feature here noted, namely, the great scarp by which descent is made from the high drift plain to the low terraces of the modern river. The conclusion is so directly opposed to the one that I have reached in the course of the present study that it has been considered with some care. In the end I am led to doubt its validity for the following reasons.

First, the occurrence of the single great scarp does not necessarily prove that the river suddenly cut its channel down from the level of the "lakes" to about that of the modern flood plain. The single great scarp is here, as in other examples of the same kind, perfectly consistent with a leisurely degradation by the river, and with the production of numerous flood plains during the degradation, provided only that the modern swinging of the river has been greater than the swinging at higher levels, whereby all remnants of the earlier flood plains shall have been destroyed. It has been shown that this is habitual with a number of streams wherever they are free to swing in loose drift of fine texture; and it appears from Emerson's description that such was the case with the Connecticut while it was sweeping away the fine silts of the Montague "lakes."

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[1] The stratified drift deposits of the Montague and other basins are interpreted as lacustrine by Emerson. Their fine texture and even stratification certainly indicate deposition in quiet water, but in the absence of any well-proved barrier between the basins of the middle Connecticut valley and the sea, there seems to be a possibility that the water bodies were of the nature of narrow-mouthed bays, with surface at sea-level, rather than normal lakes, with outflowing streams descending to sea-level.

If the reader should consult the original text of this reference, he should note that the first line of page 726 seems to have been misplaced from the bottom of that page.

Second, the leisurely lateral swinging of Saxtons and Westfield rivers at high levels, as recorded by the upper members of the terrace flights in the valleys of those tributaries of the Connecticut, show that they were not hurried in the early stages of their work of degradation; yet hurried they must have been had the master river suddenly intrenched itself in the weak drift filling of its aggraded valley. There are, to be sure, certain rock and till barriers between these terrace flights and the junction of their streams with the Connecticut, and such barriers might separate a quickly degrading trunk river from slowly degrading tributaries; but it is believed that the barriers are too low to have been encountered until after the high-level terraces had been carved.

Third, there are certain points where the Connecticut itself exhibits stepping terraces at altitudes of at least eighty or more feet above its present level. The best of these are at East Deerfield, two miles south of Turner's Falls, where the Fitchburg railroad crosses a group of terraces between the mouth of the Deerfield and the east-south bend of the Connecticut. Here an eastern profile from the high terrace south of the railroad station to the river crosses five terraces, the height of whose scarps I have estimated at 30, 25, 15, 18, and 35 feet (total, 123 feet). If the profile be taken northward from the high terrace, seven scarps are passed, including the descent from the lowest plain to the river, with heights estimated at 30, 25, 10, 5, 15, 10, and 15 feet (total, 110 feet). The locality of these terraces is openly connected with that of the high scarps in the Montague silts; and hence a leisurely process of degradation with repeated lateral swinging is probable there as well as here. The only essential difference between the two localities is that the terraces are for good reason preserved in East Deerfield, where the river has become increasingly constrained by successive discoveries of sandstone ledges, while they have been destroyed further south where the river has been free to swing at modern levels.

THE CONNECTICUT NEAR SPRINGFIELD, MASS. There are few ledges exposed hereabouts, and few stepping terraces. The high terrace that is nearly continuous on the east side of the valley from Springfield up to Chicopee, is now swept by the river for a part of its length, and within this stretch a sandstone ledge is seen in the river bank. In the southern part of Springfield there are several ledges and some exposures of bouldery till, by which the opening of the valley to the east has been restrained, and a little further south, by the mouth of Pecowsic brook, a strong ledge deflects the river to the southwest.

No ledges are found in the terrace scarps on the western side of the valley hereabouts, although several rather well-formed cusps project forward towards the river: one at the grounds of the Country club; another at the old Meeting-house north of West Springfield and a third between West Springfield and the Agawam. The Westfield river enters the main valley in the re-entrant between the second and third cusps, while south of the third cusp the Connecticut has repeatedly scoured out re-entrants from which it has been withdrawn by short-cuts or cut-offs. I am inclined to think that the Connecticut has been pushed eastward by the action of the Westfield; that it has therefore repeatedly swung westward from the Pecowsic ledges, and that the Agawam re-entrants are thus to be explained. If so, they fall into the same class with those of the Westfield in the re-entrant next west of the trap-ridge notch (page 330). The southernmost of the three free cusps on the west side of the Connecticut valley, below the entrance of the Westfield, would thus correspond with the free cusp on the south side of the Westfield, below the entrance of Little river. The other free cusps of the Connecticut may perhaps come to find an explanation in a process similar to that suggested for the free cusps between Bellows Falls and Westminster (page 341).

There is nothing in this stretch of the river to suggest a significant diminution of volume since terracing began. The frequent occurrence of high single scarps would on the other hand suggest that the river is to-day demanding a breadth of swinging as great as or greater than it ever did before.

THE MERRIMAC BETWEEN CONCORD AND MANCHESTER, N. H. The Merrimac, near Concord, has opened a broad flood plain, on which a number of former meanders are now represented by ox-bow lakes. On the east the plain is commonly bounded by a single high scarp, which the river is actively under-cutting at one point. On the west there is a single high scarp bordering part of the plain north of the city; but a few ledges appear, and the scarp is divided into several terraces as the city is entered. Passing down the valley (southward) ledges appear more frequently, the breadth of the flood plain gradually decreases, and terraces appear in increasing numbers. The valley about Concord is one of the best examples for illustration of the capacity of an unconstrained river to open a broad flood plain enclosed by strong scarps, as typified in Figures 2 and 22; while further south the valley exhibits the complete control exercised upon a swinging river by the chance discovery of ledges during the progress of degradation. This process is shown to have been gradual by the preservation of flood-plain remnants at various heights, wherever ledges are present to defend their bases; yet so complete is the destruction of the plains at intermediate levels just above Concord that one might there infer that the river had had no opportunity to swing laterally until the opening of the present flood plain was begun.

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The following Publications of the Museum of Comparative Zoölogy are in preparation: —

Reports on the Results of Dredging Operations in 1877, 1878, 1879, and 1880, in charge of Alexander Agassiz, by the U. S. Coast Survey Steamer "Blake," as follows: —

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H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea of the "Blake."
A. E. VERRILL. The Alcyonaria of the "Blake."

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of Alexander Agassiz, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

Illustrations of North American MARINE INVERTEBRATES, from Drawings by Burkhardt, Sonrel, and A. Agassiz, prepared under the direction of L. Agassiz.

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" On Arachnactis.
R. T. HILL. On the Geology of the Windward Islands.
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" The Panamic Deep-Sea Fauna.
K. BRANDT. The Sagittæ.
" The Thalassicolæ.
C. CHUN. The Siphonophores.
" The Eyes of Deep-Sea Crustacea.
W. H. DALL. The Mollusks.
H. J. HANSEN. The Cirripeds.
W. A. HERDMAN. The Ascidians.
S. J. HICKSON. The Antipathids.
W. E. HOYLE. The Cephalopods.
G. VON KOCH. The Deep-Sea Corals.
C. A. KOFOID. Solenogaster.
R. VON LENDENFELD. The Phosphorescent Organs of Fishes.
H. LUDWIG. The Starfishes.
J. P. McMURRICH. The Actinarians.
E. L. MARK. Branchiocerianthus.
JOHN MURRAY. The Bottom Specimens.
P. SCHIEMENZ. The Pteropods and Heteropods.
THEO. STUDER. The Alcyonarians.
M. P. A. TRAÜTSTEDT. The Salpidæ and Doliolidæ.
E. P. VAN DUZEE. The Halobatidæ.
H. B. WARD. The Sipunculids.
H. V. WILSON. The Sponges.
W. McM. WOODWORTH. The Nemerteans.
" The Annelids.

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GEOLOGICAL SERIES, Vol. V. No. 8.

THE FORAMINIFERA AND OTHER ORGANISMS IN THE RAISED REEFS OF FIJI.

BY R. L. SHERLOCK.

CAMBRIDGE, MASS., U. S. A.:
PRINTED FOR THE MUSEUM.
MARCH, 1903.

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March, 1903.

No. 8. — *The Foraminifera and other Organisms in the Raised Reefs of Fiji.*[1] By R. L. Sherlock.

The rocks described were obtained from various islands in the Pacific Ocean, but chiefly from the Fiji and Tonga Groups.

The specimens from Eua, Tonga Tabu, and Vavau in the Tonga Group, Makatea and Niau in the Paumotus, and Guam in the Ladrones were collected by Mr. Alexander Agassiz, and those from Niue by Prof. T. Edgeworth David, of Sydney, N. S. W. The remainder from Mango, Ngillingillah, Vatu Vara, Namuka, Yathata, Kambara, and Singatoka (in Viti Levu) all in the Fiji Group, were collected by Mr. E. C. Andrews for Mr. A. Agassiz.

The structure of the islands has been described by Mr. Agassiz in his "The Islands and Coral Reefs of Fiji." Bull. Mus. Comp. Zoöl., XXXIII., 1899, and in a series of letters published in the American Journal of Science for 1898 and 1900. Mr. E. C. Andrews has given an account of the Fiji Group in his "Notes on the Limestones and General Geology of the Fiji Islands, with special reference to the Lau Group." Based upon Surveys made for Alexander Agassiz. Bull. Mus. Comp. Zoöl., XXXVIII., 1900. Mr. J. J. Lister gives some account of the Tonga Group in his "Notes on the Geology of the Tonga Islands." Quart. Journ. Geol. Soc., London, 1891.

Raised terraces of limestone occur in each of the islands, and the question has arisen whether the limestones are composed of recent reef-building corals, or are of Tertiary age and of a different origin from the reefs now growing round the islands.

The chief interest of the terraces lies in the light they may be expected to throw on the question of the origin of atolls. On the theory of slow subsidence, the raised limestones would be composed throughout essentially of shallow-water reef-building corals. If, however, the limestones have not this composition, some other theory must be found to explain their formation in these particular cases.

The Tertiary age of certain of the rocks has been proved in two cases by the discovery of Orbitoides, and in one of these cases the rock is shown by the specific characters of the organism to be Miocene. Although a few of the rock-sections are composed of coral, and corals are also present in some others, yet in the majority of cases they are absent; Algæ and Foraminifera make up the bulk of the rocks.

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[1] Contribution from the Geological Laboratory of the Royal College of Science, London.

As regards the origin of the islands, this appears to have been somewhat as follows, according to Andrews (Bull. Mus. Comp. Zoöl., XXXVIII.): First of all in Tertiary times bedded limestones were deposited on the ocean floor on which, in many cases (*e. g.* Mango), volcanic materials, bursting through, were heaped. Wherever the accumulations reached sufficiently near the surface, corals began to grow and to form a reef. Intermittent elevation followed, each pause allowing the corals to form a new reef growing seawards on its own talus, and which, on further elevation, was transformed into a raised terrace. A succession of terraces is formed in this manner, amounting in the case of Yathata to as many as six, whilst the modern reefs, should elevation be repeated, will form another. The foundations of the terraces may be the bedded limestones and volcanic accumulations, or very often masses of rubble representing the talus derived from the terrace itself. The rubble at Niue is bedded and dips towards the sea at an angle of about 40°. It will be seen from the mode of origin that whilst the oldest terrace is the highest one, and the rubble foundations are of the same age as the terrace immediately above, the bedded limestones forming the core of the island follow the ordinary rule that the oldest bed is at the base.

The organisms found comprise fifteen genera of Foraminifera, with seven other genera doubtfully present, besides algæ, corals, echinoderms, mollusca, including Tunicata and Polyzoa, with an occasional annelid. The genera of Foraminifera are as follows:—

Miliolina, Orbitolites, Textularia, Gaudryina, Globigerina, Planorbulina, Discorbina, Truncatulina, Carpenteria, Polytrema, Tinoporus, Gypsina, Amphistegina, Heterostegina, and Orbitoides.

The genera doubtfully present are: Ammodiscus, Hastigerina, Sphœroidina, Spirillina, Pulvinulina, Calcarina and Anomalina.

For aid in the determination of doubtful forms I have to thank Mr. F. Chapman, who has given me valuable assistance.

FIJI. — MANGO. An island of composite structure composed partly of limestone and partly of volcanic rocks. It has been upheaved to the extent of about 500 feet, and there are remains of a terrace at about 200 feet, showing a pause in the elevation.

303, No. T, ht. 6 ft. The only recognizable organism is Lithothamnion. This is quite fresh although the rock has undergone dolomitization.

305, No. B, ht. 250 ft. Indistinct corals are the sole visible organisms. The rock is greatly altered.

302, No. C, ht. 280 ft. Lithothamnion is well preserved. Other organisms have been almost obliterated, but Halimeda can be distinguished.

Foraminifera : ? GYPSINA.

290 ft. This rock also is much altered. Lithothamnion is still distinct but is altered marginally.

Foraminifera : ORBITOLITES.

313, No. 23, ht. 298 ft. Lithothamnion and Halimeda are abundant. The rock has undergone considerable recrystallization, and even the Lithothamnion has been affected by the change.

Foraminifera : POLYTREMA. A small fragment of this form growing on Lithothamnion is the only foraminifer visible.

306, No. a, ht. 300 ft. The organisms are very indistinct in consequence of dolomitization. Lithothamnion, Halimeda, and corals occur.

Foraminifera : POLYTREMA PLANUM Carter. A large mass of this occurs fairly well preserved.
AMPHISTEGINA LESSONII d'Orb.
ORBITOLITES.
Textularian form.

310 ft. This section is the most interesting of the series. It shows numerous well-preserved specimens of *Orbitoides sumatrensis*, thereby proving the Miocene age of the rock. The genus has only been found in one other rock-specimen, that from Namuka, 30 ft. Polyzoa occur.

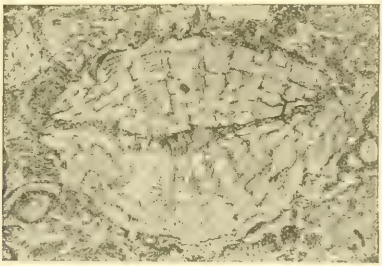

FIG. 1. Mango, 310 ft. *Orbitoides sumatrensis* Brady, × 38. The organism is of a pale straw-color.

Foraminifera : ORBITOIDES SUMATRENSIS Brady.

AMPHISTEGINA LESSONII d'Orb.
POLYTREMA MINIACEUM Pallas, sp. intergrown with Lithothamnion.
MILIOLINA.
TEXTULARIA.
? GAUDRYINA.

320 ft. A coral rock with Lithothamnion.

Foraminifera: ? GYPSINA INHŒRENS Schultze, sp. A long wandering form which may possibly be a Polytrema.

350 ft. No organisms are recognizable with certainty.

370 ft. Fragments of echinoderms are abundant; also Lithothamnion; Gasteropoda are present. The rock is fragmentary and the organisms are for the most part in a fresh condition.

Foraminifera: GYPSINA INHŒRENS Schultze, sp.
CARPENTERIA; numerous fragments.
? DISCORBINA.

316, No. B, ht. 400 ft. The organisms are very indistinct in consequence of dolomitization. As usual Lithothamnion has proved most resistant to alteration. Echinoderm fragments, corals, and Lithothamnion are recognizable besides the following

Foraminifera: AMPHISTEGINA LESSONII, d'Orb.
POLYTREMA.
? HETEROSTEGINA. Small fragments probably belong here.
? CARPENTERIA. A fragment.

NGILLINGILLAH. The island is apparently composed of coral rock 500 ft. thick, but Mr. Andrews finds that the island consists of bedded limestone, covered by coral rock and reef-débris at most 200 ft. thick. There are signs of three, or possibly four, periods of upheaval.

318, No. B, ht. 25 ft. The section consists of dolomitized coral, the crevices of which are filled with a black mud composed of organic fragments amongst which Lithothamnion, echinoderms, and a rotaline foraminifer are recognizable. Tunicate spicules are also probably present.

308, No. 43, ht. 215 ft. The rock has undergone dolomitization and the only organisms recognizable with certainty are corals.

301, No. 77, ht. 475 ft. The slide shows Lithothamnion and Polytrema growing in alternating layers. Other organisms have been obliterated by dolomitization.

Foraminifera: POLYTREMA PLANUM Carter.

VATU VARA. Of purely limestone composition. The island forms a steep pyramid 1050 feet high, surrounded by a broad flat. At least four periods of elevation are shown by terraces (three) and beach lines at the 800 ft., 600 to 700 ft., 350 ft., 25 and 15 ft. levels.

500 ft. Organisms are few in number and very indistinct. Corals, a gasteropod, Lithothamnion, and Carpenteria fragments are recognizable.

Foraminifera : CARPENTERIA.

309, No. F v. v., ht. 650 ft. The organisms have been quite destroyed by dolomitization. Lithothamnion is indicated by certain dark patches.

1000 ft. Lithothamnion and echinoderm fragments. Corals.

Foraminifera : GYPSINA.

Nummuloid form. There are numerous shattered specimens of uncertain genus, possibly Heterostegina.

NAMUKA. A small island composed entirely of limestone. It must not be confused with Nomuka, which is in the Tonga Group.

30 ft. This rock is of considerable interest as, with the exception of that from Mango, 310 ft., it is the only one containing Orbitoides. The specimen is too indistinct to enable the species to be determined, but the rock is shown by its presence to be not younger than the Miocene. Lithothamnion occurs. All the organisms are altered.

Foraminifera : ORBITOIDES.
ORBITOLITES, one very indistinct specimen.
? ANOMALINA.

75 ft. This rock much resembles the last. It contains Lithothamnion and the following : —

Foraminifera : ORBITOLITES.
Rotaline form.

162 ft. A much altered rock. Lithothamnion and Polytrema are the only organisms recognizable.

Foraminifera : POLYTREMA.

YATHATA. Partly of volcanic origin. The flat top of the island is 840 ft. above sea level and is the highest of six terraces.

800 ft. The organisms are in a fragmentary condition. They include corals, echinoderms, Lithothamnion, and Foraminifera.

Foraminifera : POLYTREMA, growing attached to Lithothamnion.
CARPENTERIA.

Kambara. The main mass of the island is composed of volcanic rocks. It is surrounded by a flat. There were at least two periods of upheaval.

250 ft. A fragmentary and fairly fresh rock. It contains Lithothamnion, numerous spines and fragments of the tests of echinoderms and a few fragments of Polyzoa.

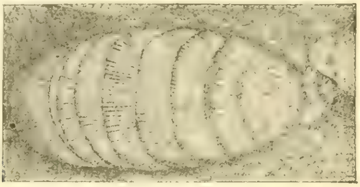

Fig. 2. Kambara, 250 ft. Lithothamnion (basal view), a fragment, × 85.

Foraminifera: Polytrema, a large mass growing on Lithothamnion, besides fragments.
Carpenteria, abundant and very well preserved.

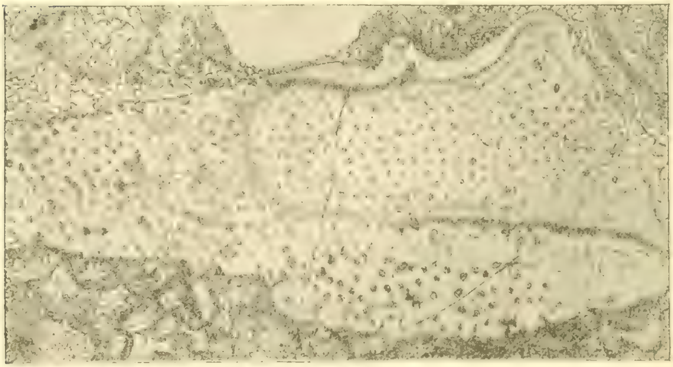

Fig. 3. Kambara, 250 ft. Fragment of Carpenteria, × 85. The organism is of a pale straw yellow color.

Amphistegina lessonii d'Orb.
Gypsina vesicularis var. monticulus Chapman.
Heterostegina depressa d'Orb, young specimens.
Orbitolites, small fragments.
Rotalian form.

SINGATOKA. This place is situated on Viti Levu, which is the main island of the Fiji Group and of a considerable size. It is largely composed of volcanic rocks, and is much older than the smaller members of the group. At Singatoka hard blue limestones, with a dip of 50°, underlie more friable limestones with a much lower dip (15°). The total thickness of the beds approaches 1500 ft.

317, No. A, ht. reef. The organisms are not numerous, but of considerable variety, including echinoderms, Lithothamnion, and Foraminifera.

Foraminifera: PLANORBULINA LARVATA? P. & J.
TRUNCATULINA.
POLYTREMA MINIACEUM Pallas, sp., one small fragment.
CARPENTERIA.
AMPHISTEGINA LESSONII d'Orb.

304, No. C, ht. 251 ft. Contains small fragments of Lithothamnion and Polyzoa.

Foraminifera: DISCORBINA.
PLANORBULINA, several specimens.
? CALCARINA, the spurs are not seen.
GYPSINA VESICULARIS P. & J., sp. var. MONTICULUS Chapman.

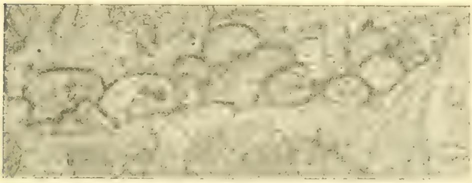

FIG. 4. Singatoka, 251 ft. *Gypsina vesicularis* P. & J., sp. var. *monticulus* Chapman, × about 50.

CARPENTERIA.
AMPHISTEGINA LESSONII d'Orb.

314, No. D, ht. 268 ft. Similar to the last. Fragmentary Lithothamnion and Polyzoa.

Foraminifera: TRUNCATULINA.
? PLANORBULINA.
CARPENTERIA, small fragments.
GYPSINA.
AMPHISTEGINA LESSONII d'Orb.
? GAUDRYINA, a textularian form, probably belongs to this genus.

NIUE (Savage Island). This island is intermediate in position between the Fiji and Tonga Groups. It contains three raised terraces at about 80 ft., 100 ft., and 200 ft., respectively, which are composed of coral rock dipping at 6° to 10°. Banks of coral débris, bedded, and dipping seawards at about 40°, form the foundations of the terraces.

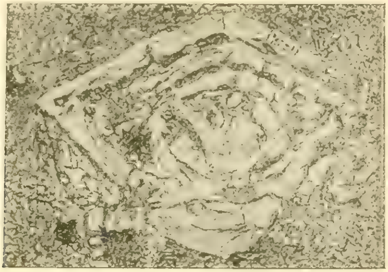

FIG. 5. Singatoka, 268 ft. *Amphistegina lessonii* d'Orb. × 85. The organism is of a pale straw-yellow color.

315, No. 3, ht. 18 ft. This rock is very fresh and the organisms well preserved, though fragmentary. Lithothamnion, echinoderms, Mollusca, and the spicules of tunicates occur.

Foraminifera : CARPENTERIA.
POLYTREMA MINIACEUM Pallas, sp.
GYPSINA.

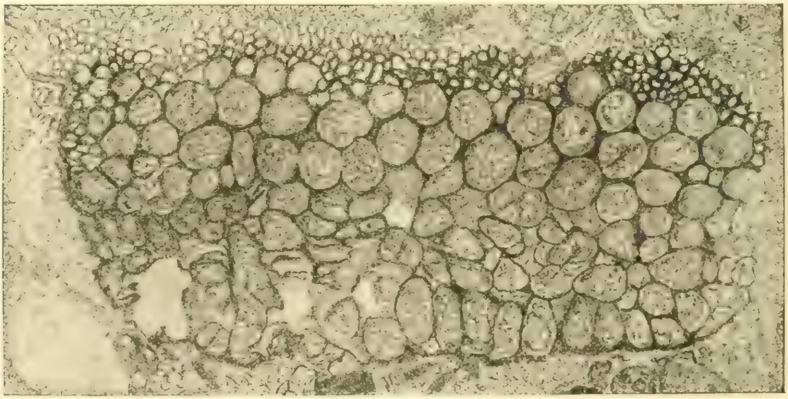

FIG. 6. Niue, 53 ft. Halimeda, × about 50.

310, No. 9, ht. 53 ft. Halimeda and alcyonarian spicules abundant. Lithothamnion and tunicates are present.

Foraminifera : CARPENTERIA, fragmentary.
ORBITOLITES, one small fragment.
POLYTREMA MINIACEUM Pallas, sp., small fragments.

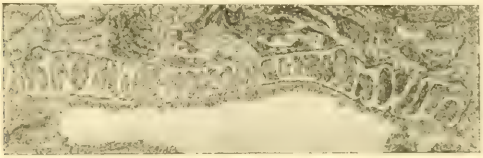

FIG. 7. Niue, Vailoa, 15 ft. Reef rock. Orbitolites, × about 45. The organism is of a burnt sienna tint.

307, No. 11, ht. 65 ft. Composed of corals with mud-filled cavities.

311, No. 12 A, ht. 70 ft. Very rich in organisms. It contains Halimeda, Lithothamnion, Gasteropoda, echinoderm fragments, and tunicate spicules.

Foraminifera : CARPENTERIA.
TINOPORUS BACULATUS Montfort, sp. abundant.

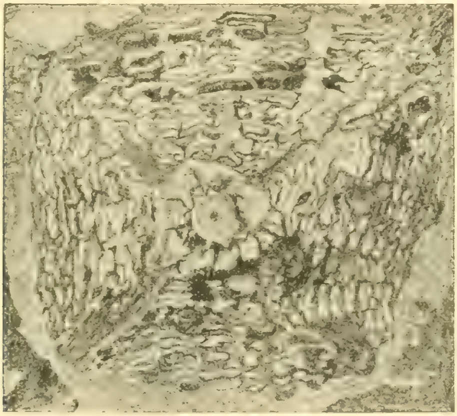

FIG. 8. Niue, 70 ft. *Tinoporus baculatus* Montfort, sp., × 90.

ORBITOLITES.
POLYTREMA, one specimen encrusts two tunicate spicules.

1st terrace, 80 ft. Portion of a mass of coral.

Upper terrace, 120 ft. Abundant Halimeda. Also echinoderms, Polyzoa, tunicate spicules, and Lithothamnion.

Foraminifera : ORBITOLITES, abundant.
CARPENTERIA, small fragments.
? POLYTREMA or ? GYPSINA, fragments.

20 A, near top of 2d terrace, 190 ft. Vailoa Niue. Tunicate spicules are very numerous. Halimeda is abundant and Lithothamnion, Gasteropoda, Polyzoa, and echinoid spines also occur.

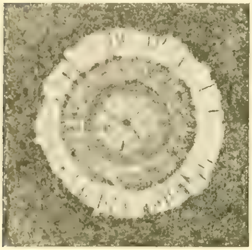

FIG. 9. Niue, Vailoa, 190 ft., near top of 2d terrace. Tunicate spicule (Leptoclinum). Large specimen, showing zonings, × 300.

Foraminifera : MILIOLINA.
ORBITOLITES, abundant.
TEXTULARIA.
SPIRILLINA (or AMMODISCUS).
TRUNCATULINA.
PLANORBULINA.
HASTIGERINA ?.
HETEROSTEGINA DEPRESSA d'Orb, numerous specimens.
POLYTREMA, fragments.

312, No. 208, ht. 200 ft. Contains corals, Halimeda, echinoderms, and Lithothamnion. Tunicate spicules are very abundant.

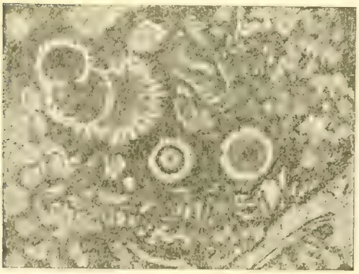

FIG. 10. Niue, 200 ft. Globigerina and spicules of Tunicata (Leptoclinum), × 85.

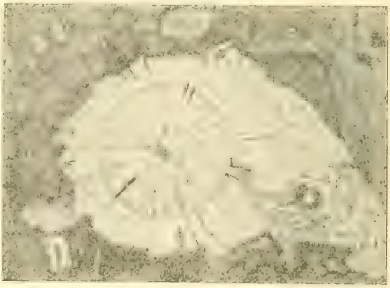

FIG. 11. Niue, 200 ft. Tunicate spicule (Leptoclinum), showing secondary growth, × 300.

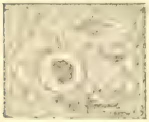

FIG. 12. Niue, 200 ft. Tunicate spicule (Leptoclinum), a very small specimen drawn to show the lower limit of size, × 300.

Foraminifera : ORBITOLITES.
GLOBIGERINA.
POLYTREMA, encrusting.
Also rotaline forms.

TONGA ISLANDS (FRIENDLY ISLANDS). TONGA TABU.—This is the largest of the Tonga group, and is twenty-two miles long. It is crescentic in shape, the convex side looking south and terminating in low cliffs. The concave side to the north is low-lying, and its shoreline represents the border of the old lagoon. The island is entirely calcareous. (Cf. J. J. Lister.)

Mt. Zion Hill, 50 ft. Contains echinoderm fragments, Gasteropoda and Polyzoa.

Foraminifera : GLOBIGERINA.
GAUDRYINA.
? HETEROSTEGINA (or ? AMPHISTEGINA).
CARPENTERIA.
POLYTREMA MINIACEUM Pallas, sp.
Also rotaline forms.

EUA. Eua is composed of two ridges running north and south, with a valley eroded between them. On the eastern side there is a limestone cliff rising in places to 1000 ft., with terraces on the projecting points. They are three in number in the north, and five in the south. The western ridge, which is also of limestone, is lower, and shows three terraces. The island is not an atoll, but an eroded platform (cf. A. Agassiz).

2d terrace, 120 ft. A few almost opaque fragments of Lithothamnion and the

Foraminifera : GYPSINA.
CARPENTERIA.
AMPHISTEGINIA LESSONII d'Orb, very abundant.
MILIOLINA, a number of specimens.
Also a broad, short, textularian form.

3d terrace, 250 ft. Halimeda, Lithothamnion, Gasteropoda. None of these are abundant.

Foraminifera : POLYTREMA.
MILIOLINA.
CARPENTERIA.

Inner Valley, 600 ft. Echinoderm fragments abundant. Lithothamnion and Polyzoa are present.

Foraminifera : ? PLANORBULINA or ? GYPSINA.
AMPHISTEGINA LESSONII d'Orb.

VAVAU. — Vavau is elliptical in outline, highest in the northern portion, where it reaches 500 ft. The southern shore is deeply indented and denudation has separated off numerous small islands from the mainland. Four terraces are visible.

1st terrace. Organisms somewhat indistinct. They consist of Polyzoa, echinoderms, and the following

Foraminifera : MILIOLINA FERUSSACII d'Orb, sp.
CARPENTERIA, somewhat indistinct.
GLOBIGERINA.
? GAUDRYINA, a textularian form, probably belongs to this genus.
GYPSINA.
POLYTREMA MINIACEUM Pallas, sp.
? GYPSINA GLOBULUS Reuss, one indistinct specimen.

2d terrace, ? 310 ft. Lithothamnion, Polyzoa, Gasteropoda.

Foraminifera : TEXTULARIA.
GYPSINA, numerous specimens.
CARPENTERIA.
POLYTREMA MINIACEUM Pallas, sp.
MILIOLINA.

2d terrace, ? 350 ft. Polyzoa, echinoderm spines, Lithothamnion.

Foraminifera : MILIOLINA, several specimens.
CARPENTERIA.
? GLOBIGERINA CONGLOBATA Brady (or possibly SPHŒROIDINA BULLOIDES), one specimen only.
AMPHISTEGINA LESSONII d'Orb, one specimen.

2d terrace, 360 ft. Numerous fragmentary organisms embedded in a crystalline matrix. Lithothamnion is the most abundant organism. Echinoderms, Gasteropoda, and annelids (?) are alsó present.

Foraminifera : POLYTREMA MINIACEUM Pallas, sp.
CARPENTERIA.
AMPHISTEGINA LESSONI d'Orb.
GLOBIGERINA, one specimen enclosed in an annelid (?) tube.
GYPSINA.

3d terrace. Highest point, north shore. The only organisms are alcyonarian spicules, and of these the rock is mainly composed.

PAUMOTUS GROUP. MAKATEA (METIA or AURORA I.). An elevated mass of coraliferous limestone with a comparatively narrow shore platform cut from the base of the cliffs. It is the highest member of the group, reaching 230 ft.

2d terrace. No organisms.

Basin, 150 ft.–175 ft. Lithothamnion and Mollusca, the former abundant.

Foraminifera : POLYTREMA MINIACEUM Pallas, sp.
POLYTREMA PLANUM Carter. The two species of POLYTREMA are encrusting forms, the P. PLANUM is here growing on P. MINIACEUM, and the latter on Lithothamnion. The three organisms make up the bulk of the rock.
CARPENTERIA.
GYPSINA.
? AMPHISTEGINA, one specimen, which may possibly be HETEROSTEGINA.

3d terrace, 200 ft. A coral rock which has undergone alteration.

NIAU. — This island, like the others of the group, has been greatly denuded. The Tertiary limestones do not occur at a higher level than about 16 ft. It is the only member of the group which possesses a lagoon shut off from the sea.

20 ft., half-way across the rim. A coral rock, a fragment, apparently of a mollusc, occurs, but alteration has rendered it indistinct.

THE LADRONES. GUAM. — The northern half consists of raised limestones, which form vertical cliffs on the eastern side, 109 to 300 ft. high. In the southern half, volcanic rocks, in places, burst through the limestones. This part of the island reaches 1000 ft.

Mt. Makawia, near the summit. A fragmentary rock made up of organisms broken to a uniform small size. They comprise Lithothamnion, Polyzoa, and

Foraminifera : MILIOLINA, fairly numerous.
TEXTULARIA.
TRUNCATULINA, numerous specimens.
? SPIRILLINA, one doubtful specimen.
? CARPENTERIA, numerous, rather indefinite fragments.
GYPSINA.
POLYTREMA.

Of the forty-seven rock-sections examined, Lithothamnion occurs in thirty-five, and is decidedly the most abundant and most widely distributed organism. Many of the slides in which it is not found have been dolomitized, and any organisms present have been removed. Probably Lithothamnion was present in some of these rocks originally. It should be mentioned that the term Lithothamnion is used throughout in the older and wider sense, and not as a generic name.

Halimeda, the other calcareous alga present, is much less widely distributed. It occurs in nine sections, coming from Mango, Niue, and Eua. It is much less stable than Lithothamnion, and this may account to some extent for its more limited distribution.

Echinoderm fragments (largely echinoid spines) occur in seventeen of the specimens, and take an appreciable part in the composition of the rocks. Polyzoa were found in twelve slides from eight of the fourteen islands. They are most abundant in the Vavau rocks.

Corals occur in fifteen sections, being represented in two cases by alcyonarian spicules only. Since they undergo alteration rather easily, they may have been present originally in some of the altered rocks, but even taking this into account, they play a much less important part in the formation of the limestones than might be expected. Moreover, a large proportion of the rocks were obtained from terraces where the corals seem to be especially abundant, yet the actual bulk of the terraces compared with the rest of the limestones is not great.

Of the Foraminifera, Carpenteria occurring in nineteen sections, and Polytrema in twenty-one, are the most widely distributed and also the most numerous individually. Carpenteria has probably had an even wider distribution than appears, as it seems to undergo alteration fairly easily. The genus Polytrema is commonly represented by *P. miniaceum* Pallas, sp., but *P. planum* Carter also occurs. Both forms are found at times intergrown with Lithothamnion, forming a mass consisting of layers of the different organisms alternating. Polytrema, however, encrusts various objects besides Lithothamnion.

Gypsina was found in eleven sections, and is often very abundant. Orbitolites occurs in ten sections, but is only abundant in the Niue rocks. As a rule, not more than one specimen occurs in a slide. In sections it possesses a burnt sienna color which is characteristic, although in some cases where alteration has taken place it is black and opaque. Miliolina occurs in eight sections, but does not make up a considerable part of any of the rocks. It is commonest in Eua and Vavau sections.

Amphistegina occurs in eleven slides, and is often abundant, as is the case in the rock from Eua, 120 ft.

Although rotaline Foraminifera occur in many of the slides, no form is common. The most generally occurring genera are Planorbulina and Truncatulina. Globigerina occurs in four slides. Orbitoides is of especial interest, as it is not found in rocks younger than the Miocene. Individuals are very numerous in the section from Mango, 310 ft., and it is noteworthy that the genus is entirely absent from the other Mango specimens examined.

The Niue rocks are characterized by the great number of tunicate spicules which they contain. The first described occurrence of these organisms as fossils was in the Pliocene of St. Erth, Cornwall, where Messrs. Kendall and Bell found spicules referred by Dr. G. J. Hinde to Leptoclinum.[1] Professor Herdman had previously pointed out that calcareous spicules occurred in many genera of Tunicata, and were as capable of preservation as the aragonite skeletons of other organisms.[2] As, however, with the exception of the St. Erth beds above-mentioned, they do not seem to have been found in the fossil condition, their occurrence in the coral reefs of Niue becomes of interest.

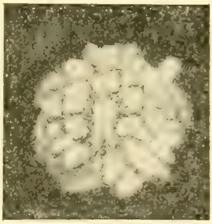

FIG. 13. Niue, Vailoa, 15 ft. Tunicate spicule (Leptoclinum), surface view, × 300.

Although Niue (Savage Island) is situated between the Tonga and Fiji Groups, and the rocks of all three places resemble each other in structure and composition, the tunicate spicules appear to be confined to Niue (with the doubtful exception of Ngillingillah). They also occur, however, in the rocks from Christmas Island collected by Dr. C. W. Andrews, and in the Funafuti boring described by Dr. G. J. Hinde. In all three cases, Niue, Christmas Island, and Funafuti, the spicules seem identical and belong to the same genus, Leptoclinum Milne Edwards, as occurs at St. Erth.

The number of spicules present in the rocks also varies widely. All the slides which are not simply sections of a coral mass, show some spicules, but they are particularly abundant in the black mud. In many cases, circular areas of clear granular calcite occur having the usual size of the spicules, but showing no structure. These clearly represent the spicules which have been altered into calcite and their structure destroyed. They are found, for example, in sections of the talus, where one would expect alteration to take place readily from the fragmentary and therefore porous nature of the rock. It is probable from this that tunicates took a more important part in the composition of the reefs than appears at first sight, owing to the ease with which aragonite organisms are obliterated. The value of tunicates as rock-formers may be estimated in a particular case by finding the fraction of the surface area of a section of the rock covered by the spicules. Choosing a section in which the tunicates were especially abundant, they were found to form approximately 2 per cent of the whole mass. In most of the slides they form a smaller proportion than this, and about .5 per cent may be taken as the average for the Niue rocks.

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[1] Quart. Journ. Geol. Soc. Lond., XLII. pp. 201–215.

[2] Proc. Geol. Soc. Liverpool, 1884–85, p. 42.

In the Niue specimens the spicules are circular in sections and show a clear outer zone of radiating fibres surrounding a dark granular area. In many specimens the centre of the granular portion has a distinctly radiating structure, and is more translucent than the remainder of the central area, but in others the granular area extends to the centre. The composition of the spicules is shown to be aragonite, by staining them with cobalt nitrate.[1] By this method, in which a polished slice of rock is boiled with ordinary cobalt nitrate solution for some time, aragonite is stained pink, but calcite is not affected, unless the boiling has been continued for a very long time, when it may stain blue. The granular portion of the spicule stains pink readily, but the outer zone stains only on long boiling. This shows that the whole is aragonite, but that there is some difference between the zones, probably due to a difference in the state of aggregation.

From the fact that the sections are invariably circular, the spicules must be spherical. In a few cases the surface is seen, and appears tuberculated, the bases of the relatively large but low tubercles being in close contact.

The spicules vary very greatly in size, as is shown by the figures, which are drawn to the same scale. Many of the smallest sections show only the outer fibrous zone, and are, therefore, probably tangential sections of large spicules. But others, such as the one figured, show the central granulated area occupying the same proportion of the whole as in the larger forms, and these must be small spicules. The diameter varies in length from $\frac{1}{12}$ to $\frac{1}{300}$ mm. (about $\frac{1}{300}$ to $\frac{1}{1500}$ in.). In a few cases, as shown by staining, the outermost fibrous zone is absent.

Some recent spicules of Leptoclinum from Anticosti (Canada), very kindly lent by Dr. G. J. Hinde for comparison, are very closely similar to the Niue specimens. The only difference is that the Anticosti spicules show in optical section slightly projecting tubercles which are not seen in the great majority of the Niue spicules. But in a few of the latter there are indications of the tubercles, especially in those seen in surface view, as already mentioned. Dr. Hinde has isolated spicules from the sandy material of the Funafuti boring. A few of these have long spines and closely agree with the spicules of Leptoclinum figured by Professor Herdman in his Challenger Report. The remainder are covered by short tubercles (like the recent specimens from Anticosti), but probably belong to the same species as the spiny ones, for Professor Herdman has shown that two varieties do exist in the same animal in the case of some recent species. The spicules in the Funafuti rock-sections are identical with the Niue forms, so that these latter may be taken as belonging to the genus Leptoclinum.

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[1] W. Meigen. Centralblatt Min., 1901, pp. 577–578.

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